BUCK BOOST CONVERTER BASED BATTERY CHARGE BALANCING CIRCUIT

A DISSERTATION

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ELECTRICAL ENGINEERING
(With Specialization in Power Electronics)

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CANDIDATE’S DECLARATION

I hereby declare that the work carried out in this dissertation entitled “**BUCK BOOST CONVERTER BASED BATTERY CHARGE BALANCING CIRCUIT**” submitted in partial fulfillment of the requirements for the award of the degree of Integrated Dual Degree (IDD) in Electrical Engineering with specialization in Power Electronics, submitted to the Department of Electrical Engineering, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out under the guidance and supervision of Dr. S. P. Srivastava, Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee and all the works embodied in this thesis has not been submitted elsewhere for the award of any other degree.

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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ABSTRACT

A large number of direct current applications make use of rechargeable DC batteries made up of a string of series connected cells. Charge imbalance of cells in such battery systems is typical in series connected battery strings. Usually, the individual cells in a battery have somewhat different capacities and may be at different levels of state of charge (SOC). Imbalanced cells can directly affect the operation of the battery pack and life of individual cells. It is imperative to use circuits that balance cells or maintain a check on the degree of imbalance during the charging or discharging of battery.

Starting with the general description of battery operated systems and the common challenges faced during battery operation, the problem of battery imbalance is explained in this thesis. The reasons for imbalance in batteries, the need for charge balancing and popular charge balancing techniques used to tackle this problem are further elaborated. The design, operation and control of a DC-DC converter based active balancing circuit are discussed in detail. The balancer circuit discussed here transfers the energy from fully charged battery cell to the weakest charged battery in a fashion similar to buck-boost operation. This operation maintains batteries at the same charge and voltage level. The design methodology and simulation results that act as proof of concept, are presented for a system consisting of two lead acid batteries connected in series.

The working of the circuit is further demonstrated by building a hardware prototype and testing it. A microcontroller based control is implemented to provide PWM signals to the switches in the circuit. The hardware results match with the expected theoretical predictions and qualitatively verify the working of the circuit.

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LIST OF NOMENCLATURES

DC	Direct Current
SOC	State of Charge
OCV	Open Circuit Voltage
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride
Li-ion	Lithium Ion
i_L	Instantaneous current
D	Duty Cycle
T_s	Switching time period
L	Inductance of the inductor
Q	Charge flown in the process
S_{1d2c}	Switch active in the path for discharging battery 1 and charging battery 2

CHAPTER 1: INTRODUCTION

1.1 Research Motivation

The utility of battery operated DC systems has risen steadily for the past few decades. Many factors have contributed to this trend. For a large amount of time the primary utility for batteries was consumer electronics devices, portable instrumentation and start, lighting and ignition (SLI) batteries in automobiles. In recent times, batteries are being used to interface electric grids with renewable energy systems using large Battery Energy Storage Systems (BESS). Simultaneously a rapid development in electric vehicle and related technologies has caused an increase in demand for batteries for vehicle traction in electric vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles. Moreover, with the advent of new technologies such as wearable computing, Internet of Things, robotics etc., demand for batteries has further increased.

Battery operated systems are expected to be ubiquitous in the future. Most applications of batteries require secondary (rechargeable) batteries. High energy systems often consist of multiple series connected cells for storing energy. As a result, battery systems are often designed in the form of modules to deal with single cells.

Although batteries are very convenient to use, they suffer from many limitations with regard to health, lifetime, performance degradation, requirement of appropriate operating conditions and other potential operating hazards. When a large number of series connected cells are involved, the cells have a tendency to accumulate different levels of changes overtime. This causes the cells to get unbalanced. To ensure a healthy battery pack that lasts for a longer time and one that can be fully utilized for high efficiency, the individual cells of a battery need to be balanced as far as possible.

Most rechargeable battery setups have a Battery Management System (BMS) for monitoring their health, calculating related data and controlling its environment. One of the most important components of a BMS is a batter balancer. The function of the battery balancer is to maintain the component cells of a battery pack at the same State of Charge (SOC). The balancer is often active when the battery pack is being charged or discharged. Battery balancing technology is broadly classified into active balancing and passive balancing. For a collection of unbalanced series connected cells in a battery, passive balancing technology wastes the excess energy present in the cells with higher state of charge. On the other hand, active balancing involves transferring excess energy of the pack from the higher charged cells to the lower charged cells.

Battery balancing remains a challenging problem in the design of Battery Management systems. As explained in the remainder of the thesis, balancing the individual cells of the battery improves the health and lifetime of a battery significantly. As explained above, improving battery technology is a highly lucrative task, can turn to be extremely impactful and hence forms the motivation for this thesis.

1.2 Literature Review

The topic of battery balancing circuits is relatively new and literature specific to this topic is scarce. Most of the literature available on power converter based battery balancing technologies has been reviewed

- P. Cassani, S. Williamson, explain the significance of battery balancing in their work for Plug in Hybrid Vehicles[5].
- In 2003, Chin S. Moo *et al* was one of the earliest works to demonstrate a charge equalizer circuit for series connected batteries [2]. The circuit used buck boost converter as individual charge equalizer and operated in closed loop mode. Similar work is found throughout literature with other dc-dc converters such as Cuk[8] and flyback[10] converters.
- A 2009 publication on a buck boost type battery balancer by Sang-Hyun Park, Tae-Sung Kim, Jin-Sik Park, Gun-Woo Moon and Myung-Joong Yoon [6] introduced the buck boost converter based battery balancing circuit. This circuit has been studied in extensive detail in this thesis.
- A 2008 publication by Jian Cao, Nigel Schofield and Ali Emadi provides the most comprehensive review of all the different battery balancing methods [1]. In this paper, a brief discussion of almost all battery balancing circuits can be found.

1.3 Objective of the Thesis

This thesis presents a study of a buck boost converter based active battery balancing circuit. The discussions include the investigation of circuit operation, design methodology, and implementation for balancing cells of given state of charge. It also presents a brief review of popular battery balancing techniques. It covers the following areas in detail:

- Reviewing the state of the art in battery balancing techniques, including areas of passive and active battery balancing.

- Understanding buck boost converter based circuit topology, operation and basic inductive shuttling behavior.

- Developing the design methodology to design circuit components and switching parameters.

- Modeling and simulation of the circuit for a system of two unbalanced batteries. Exhaustive analysis of the circuit for various starting conditions, to obtain a proof of concept for the circuit.

- Development of hardware prototype for verification of simulation results.

1.4 Thesis Organization

Chapter 1 covers the research motivation, literature survey, objectives of the thesis and organization of the report.

Chapter 2 contains a discussion of battery operated systems, and definitions of quantities used to asses batteries. It also includes a brief description of the various challenges faced in operating battery operated systems including battery cell imbalance. This is followed by a review of battery balancing circuits including a brief description of each circuit, passive and active. This chapter also explains the need for battery balancing.

Chapter 3 discusses the buck boost converter based battery balancing circuit in detail covering all aspects of circuit topology, operation, design considerations involved in the circuit. In addition, this chapter explains the control algorithm for running the circuit.

Chapter 4 presents the results and analysis of the MATLAB simulation results for the buck boost converter based battery balancing circuit.

Chapter 5 covers the hardware implementation of the prototype and related documentation, i.e circuit schematics for the switches, drivers, sensors and controller as well as discussion of hardware results.

Chapter 6 presents the conclusive remarks of the work performed in the thesis along with recommendations for future scope of work that can be done.

CHAPTER 2: BATTERY OPERATED SYSTEMS

In this chapter, a general introduction to battery powered systems is presented. Applications of rechargeable batteries, quantities used to assess battery performance and a brief description of challenges faced with operation of batteries is discussed.

2.1 Battery Applications

A battery is an electrochemical device usually made of up of multiple electrochemical cells connected in series. Batteries are used for storage of electric energy. Primary batteries are used once and must be discarded hence. Secondary batteries can be recharged to full charge and used multiple times. The work presented here deals only with rechargeable batteries. Based on the type of compounds used for electrodes and electrolytes, batteries are said to have different ‘chemistries’. Most commonly chemistries of secondary (rechargeable) batteries are lead acid, nickel-cadmium (NiCd), nickel metal hydride(NiMH) and lithium ion(Li-ion) cells. Each battery chemistry has unique characteristics that manifest itself in battery charge-discharge behavior and other performance parameters.

In many low power portable electronics devices such as digital computers, electronic instrumentation, consumer electronics etc. batteries are used as the primary source of power. For much larger power applications, batteries are often used as emergency power supplies (uninterruptible power supplies). In addition to this lead-acid and Lithium ion batteries are rapidly becoming popular in their use in grid connected Battery Energy Storage Systems (BESS). For interfacing dc loads and renewable energy sources with the grid, for storing excess energy when production exceeds consumption and for supplying stored energy to assist the grid when consumption exceeds production, batteries are most effective way of storing energy.

In addition to local energy storage batteries also form an essential part of automobiles. In fuel based automobiles, lead-acid batteries are most commonly used for starting, lighting and ignition (SLI Batteries). These batteries are used primarily to assist in starting spark plugs and supporting automobile electronic circuitry. With the advent of Electric Vehicles (EVs), Hybrid Electric

Vehicles (HEVs) and Plug-in Hybrid Vehicles (PHEVs), batteries have found use in vehicle traction applications.

It can be noted that almost all secondary battery applications, require multiple series connected cells to meet the energy requirements. This limitation arises mainly due to the limiting energy density of single electrochemical cells as will be seen in the coming sections.

2.2 Battery Specifications and Health Parameters

Batteries and cells are commonly identified with their open circuit voltages. However, a large number of parameters determine the performance of a certain battery. This section provides an introduction to the terminology used to specify and compare cells. It provides a basic background, defines the variables used to characterize battery operating conditions, and describes the manufacturer specifications used to characterize battery nominal and maximum characteristics.

All terminology and definitions are included here for ready reference.

- **State of Charge (SOC)(%)** – An expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time.

- **Depth of Discharge (DOD) (%)** – The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge to at least 80 % DOD is referred to as a deep discharge.

- **Terminal Voltage (V)** – The voltage between the battery terminals with load applied. Terminal voltage varies with SOC and discharge/charge current.

- **Open-circuit voltage (V)** – The voltage between the battery terminals with no load applied. The open-circuit voltage depends on the battery state of charge, increasing with state of charge.

- **Internal Resistance** – The resistance within the battery, generally different for charging and discharging, also dependent on the battery state of charge. As internal resistance increases, the battery efficiency decreases and thermal stability is reduced as more of the charging energy is converted into heat.

- **Nominal Voltage (V)** – The reported or reference voltage of the battery, also sometimes thought of as the "normal" voltage of the battery.

- **Cut-off Voltage** – The minimum allowable voltage. It is this voltage that generally defines the "empty" state of the battery.

- **Capacity or Nominal Capacity** (Ah for a specific C-rate) – The coulometric capacity, the total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage. Capacity is calculated by multiplying the discharge current (in Amps) by the discharge time (in hours) and decreases with increasing C-rate.

- **Energy or Nominal Energy** (Wh (for a specific C-rate)) – The "energy capacity" of the battery, the total Watt-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage. Energy is calculated by multiplying the discharge power (in Watts) by the discharge time (in hours). Like capacity, energy decreases with increasing C-rate.

- **Cycle Life** (number for a specific DOD) – The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the rate and depth of cycles and by other conditions such as temperature and humidity. The higher the DOD, the lower the cycle life.

- **Specific Energy (Wh/kg)** – The nominal battery energy per unit mass, sometimes referred to as the gravimetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery weight required to achieve a given electric range.

- **Specific Power (W/kg)** – The maximum available power per unit mass. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery weight required to achieve a given performance target.

- **Energy Density (Wh/L)** – The nominal battery energy per unit volume, sometimes referred to as the volumetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery size required to achieve a given electric range.

- **Power Density (W/L)** – The maximum available power per unit volume. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery size required to achieve a given performance target.

- **Maximum Continuous Discharge Current** – The maximum current at which the battery can be discharged continuously. This limit is usually defined by the battery manufacturer in order to prevent excessive discharge rates that would damage the battery or reduce its capacity. Along with the maximum continuous power of the motor, this defines the top sustainable speed and acceleration of the vehicle.

- **Maximum 30-sec Discharge Pulse Current** –The maximum current at which the battery can be discharged for pulses of up to 30 seconds. This limit is usually defined by the battery manufacturer in order to prevent excessive discharge rates that would damage the battery or reduce its capacity. Along with the peak power of the electric motor, this defines the acceleration performance (0-60 mph time) of the vehicle.

- **Charge Voltage** – The voltage that the battery is charged to when charged to full capacity. Charging schemes generally consist of a constant current charging until the battery voltage reaching the charge voltage, then constant voltage charging, allowing the charge current to taper until it is very small.

- **Float Voltage** – The voltage at which the battery is maintained after being charge to 100 percent SOC to maintain that capacity by compensating for self-discharge of the battery.

- **(Recommended) Charge Current** – The ideal current at which the battery is initially charged (to roughly 70 percent SOC) under constant charging scheme before transitioning into constant voltage charging.

- **Charge/ Discharge Characteristics –** This is a graph of the battery terminal voltage vs percent of capacity remaining (or SOC). Different curves are formed for different charging/discharging currents. It is found that pulsed current in batteries tends to give better capacity as compared to constant current. The discharge characteristics are extremely sensitive to duty cycle variations at the same current.

- **Temperature Characteristics --** These are the graphs of terminal voltage vs discharge time at a certain discharge current at various temperatures. Cell performance thus becomes sensitive to operating temperatures.

- **Self- Discharge Characteristics --** The self-discharge rate is a measure of how quickly a cell will lose its energy while sitting on the shelf due to unwanted chemical actions within the cell. The rate depends on the cell chemistry and the temperature.

We would expect an ideal battery to have ideal specifications such as constancy in terminal voltage, flat/identical discharge/charge curves for various currents, high energy density and high power density etc. however practical batteries have limitations depending on their chemistry, operating conditions, types of load as well as environment as seen in the next section.

2.3 Challenges faced in Battery Operation

Electrochemical cells by themselves have some inherent limitations. These limitations give rise to inefficiencies and constraints when being operated. Although batteries are meant to be utilized as a source of stored energy, there is a limit to the amount of power output that the battery can provide. Depending on capacity and electrochemistry, batteries have an upper limit on the charge/ discharge currents. Charging the battery at higher currents can reduce the life of the battery gradually or even cause permanent failure via thermal runaway. Many batteries especially Lithium ion, require protection circuits to protect from overcurrent, overcharging and excessive temperature rise.

A common phenomenon in batteries is self-discharge. Even when no external load or charging circuit is connected to the battery, due to internal chemical reactions between the electrodes, the stored charge of the batteries reduces. This is not a defect, but a general characteristic of every practical battery. The rate of self-discharge depends mainly on battery chemistry, current state of charge, charging current and ambient temperature. The energy loss is asymptotical, meaning that the self-discharge is highest right after charge and then tapers off. Self–discharge reduces the shelf life of batteries. When these batteries are put to actual use, they have less than full charge. A common method to keep self-discharge rates low is to keep the battery at low temperatures.

The overall performance and usable capacity of a battery deteriorates with time. This phenomenon is called cell ageing. This happens due to unwanted physical and chemical reactions occurring at the electrodes and electrolyte. Ageing process unlike self-discharge is generally irreversible and causes permanent deterioration. Different mechanisms are responsible for the ageing of different cell chemistries. Oxidation of electrodes, formation of a resistive compound on electrode surface, corrosion of electrodes etc. are some examples of mechanisms that result in permanent loss of usable capacity.

Almost all battery parameters are affected by operating temperature. All reactions occurring within a battery during charging or discharging are essentially chemical reactions whose rate will slow down at lower temperatures. As a result the discharge characteristics, self-discharge characteristics, ageing process and usable capacity are all affected by temperature. Rise in cell temperatures may lead to overheating, which is major contributing factor in nearly all cell failures. Working with large cell packs becomes a problem when different cells are at different temperatures. As temperature changes take place, it is challenging to maintain a strict load current profile if required by the load. Similarly, extremely low temperatures affect the physical and chemical properties of the battery electrodes/electrolytes and the internal resistance of the cell leading to poorer performance or loss of capacity.

In a battery pack consisting of many cells connected in series, the performance deterioration of each cell affects the overall performance of the battery pack. As a result high performance battery packs usually come with a Battery Management System (BMS). A sophisticated battery management system can serve many functions, primarily:

- Protection circuits that prevent damage of the cells.
- Maintaining optimum shelf life conditions to prolong battery life.
- Maintain the battery in a state in which it can fulfill the functional requirements of the application for which it was specified.

One of the prominent issues occurring with all battery packs consisting of multiple series connected cells, is the unbalancing of component cells. This phenomenon is explained in detail in the following sections.

2.4 Imbalance in Battery Cells

As discussed in sections above, the state of charge (SOC) of a battery is the percentage of remaining cell charge. It is a true measure of the capacity of the cell. When a cell is being charged/discharged with some current, the terminal voltage is a misleading indicator of cell capacity. At the same state of charge, different currents will elicit different terminal voltages for the battery. A SOC difference is the only cause for cell voltage differences if no current is flowing, known as open circuit voltage (OCV). Indeed, there is a simple correlation between SOC and voltage for any battery chemistry in the form of OCV = f (SOC,T), where SOC is the state of charge and T is temperature. The form of the function is different depending on the chemistries, but in general it is clear that for a given difference in SOC, you get some difference in voltage.

When the component cells of a battery pack are at different SOCs with respect to each other there exists an imbalance in battery cells. Some cells will be more charged than others. This is typical of any battery pack consisting of series connected cells. Many factors are responsible for imbalance between cells in a battery pack, some of these are due internal mechanisms of the battery and others are due to external circuit processes:

i. Variance in manufacturing process may lead to production of cells with different capacities. This problem is more prominent in Lithium ion cells, as the production process involves cell cycling and defects in cell cycling process and related instrumentation are common.

ii. Difference in self-discharge rates, which are highly dependent on temperature. Different cells placed at different temperatures have different internal resistances. Also, temperature directly affects rate of electrochemical activity. As a result, hotter cells tend to self-discharge faster than cooler ones.

iii. SOC imbalance can be also caused by uneven leakage to the battery pack circuit from different cells. In a battery pack, some of the cells may be used to power protection circuits, temperature and current sensors and other monitoring instrumentation in addition to the load. As a result some cells are discharged more than others and an imbalance is created.

iv. Some cells in a battery pack may be from an older production batch as compared to others. As a result of ageing, there might be an inherent difference in the capacity of component cells of a battery.

2.5 Need for Battery Balancing

Consider a battery pack consisting of series connected cells each at different states of charge. Some of the cells are at a lower state of charge compared to others and present a lower capacity than rated. When this battery pack is discharged, the weakest cells (cells with lowest initial SOC) will fully discharge earliest. Although others cells can still be used to full capacity, the discharging current needs to halt in order to avoid over discharge of the weakest cells. Similarly, when charging, the strongest cells (cells with higher initial SOCs) will get charged to full capacity earlier than others. If the charging process is not stopped, these cells will get overcharged and this seriously affects the health of the cell. The problems that may arise in an unbalanced battery pack are elaborated as follows:

i. **Safety**: In an unbalanced battery pack, stronger cells will get charged to full capacity earlier than weaker cells. In order to charge all remaining cells to full capacity, one may continue to charge the battery pack. However, this will cause the stronger cells to get overcharged. This reduces the life and usable capacity of all batteries. Excessive over charging can also cause degradation of electrodes/electrolyte, overheating and also result in permanent failure. For some battery chemistries such as Li-ion, when overcharged, they can undergo thermal runaway, melting the battery pack and the device it is powering. Thus overcharging must be avoided for safe operation.

ii. **Longevity**: For a given battery, if the rated maximal recommended charging voltage is exceeded even a little, it will cause accelerated degradation of total battery capacity. To ensure long life, overcharging and under charging needs to be avoided.

iii. **Incomplete charging of the pack**: Consider the process of charging an unbalanced battery pack. A protector circuit does its job and charging stops when just one cell gets close to unsafe conditions (to prevent overcharging). Now we have successfully prevented thermal runaway, but all of the other cells now have lower voltages and are not fully charged. Less pack voltage means less pack energy.

iv. **Incomplete use of pack energy**: When discharging an unbalanced battery pack, one cell could have too low a voltage compared to others when the pack is close to the end of discharge. A pack protector will prevent over-discharge by stopping the discharge of the whole pack when one cell voltage goes below the cell under-voltage threshold. This means that all other cells are still at higher voltages and have energy left. The pack still has energy, but the device can no longer be used because of one misbehaving cell.

From this discussion, it is evident that imbalance in battery cells, presents a problem in the desired operation of the battery pack in a particular operation. Imbalance in cells tends to increase over time, and presents more serious problems during run time. For optimum performance and maintenance of the battery pack, it is essential to have a dedicated battery charge balancer. In the following sections, some of the popular charge balancing circuits are presented along with their balancing methodology and brief description.

2.6 Battery Balancing Circuits

Most battery systems use a balancing circuit as part of the Battery Management System (BMS). The function of these balancing circuits is to equalize the SOC (and voltage) of the individual cells of the battery. A good number of popular balancing circuits can be found in literature. Battery charge balancing techniques can be broadly classified into passive and active balancing on the basis of method of energy transfer-explained in the following section.

2.6.1 Passive Balancing Circuits

To balance a set of series connected imbalanced cells by passive balancing methods, the excess energy/charge of higher charged batteries is wasted or dissipated to prevent them from overcharging. These are dissipative techniques that find the cells with the highest charge in the pack, indicated by the higher cell voltage, and remove excess energy by wasting it away, for example through a bypass resistor. The popular methods that fall under this category are mentioned below:

i. Lead-acid and Nickel based batteries can be brought into overcharge conditions without permanent cell damage. When the overcharge is not very severe, the excess energy is released by increased cell body temperature. When the overcharge is too much, the energy will be released by gassing via the gassing valve equipped on the cells. This is the natural method of balancing a series string of such cells. However, this method is effective on for a few number of series connected cells. As the number of cells increase this circuit presents more problems. Generally, this method is a cheap solution for lead-acid and Nickel based batteries.

ii. The most popular passive balancing method involves dissipative shunting through resistors. One simple implementation of cell balancing uses a MOSFET in parallel with each cell and controlled by a comparator output for simple voltage-based algorithms that turn on the bypass FETs during the onset of voltage differences, or controlled by a microcontroller for more complex and effective algorithms that can work continuously regardless of variations in the voltage.

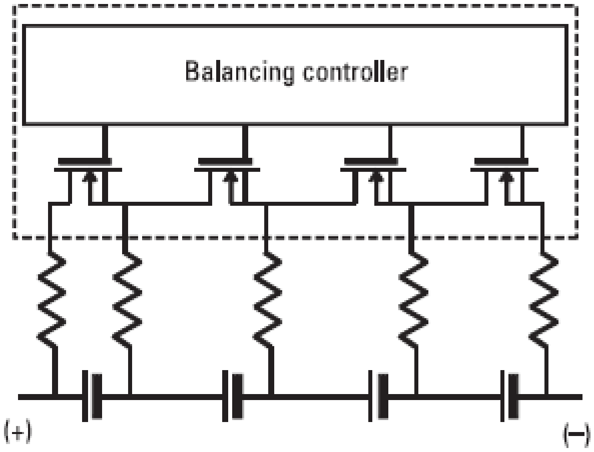

Figure 2.1 Dissipative shunting through resistors

Source: [3]

The idea of here is that during the charging process the energy in the highest charged cells is dissipated through the resistor until the weaker cells get charged. The basic function of the balancing controller is to sense the SOCs of individual cells, to identify the highest charged cells and to switch the corresponding switches for appropriate time so as to dissipate/bypass excessive energy until the remaining cells get fully charged. More sophisticated algorithms may carry out switched dissipation at regular intervals.

Passive balancing circuits are widely used in many Battery Management Systems. They are available as a black box for low power electronics applications. Even for high power applications such as electric vehicle batteries, passive balancing for large battery packs is carried out. However, it can be inferred from the discussion above that passive balancing methods has its own drawbacks. Passive balancing circuits are lossy as they waste away the excess energy as heat. Other than resulting in power loss, this also creates an issue of thermal management in the battery pack and related circuitry. Most implementations of this circuit operate only at the end of charging cycle.

2.6.3 Active Balancing Circuits

The basic idea of active balancing is to use external circuits to actively transport energy among cells so as to balance the cells. Active cell balancing circuits remove charge from one or more higher charged cells and deliver the charge to one or more low charged cells. The active balancing method can be used for most modern battery systems because they do not rely on the characteristic of cells for balancing.

Unlike passive balancing circuits, active balancers circulate energy amongst the cells and the battery pack to ensure equal charge among cells. There is no loss of energy in this case. All of the active cell balancing methods use some sort of charge routing or exogenous storage device (typically a capacitor, inductor, or a combination of both) to shuttle energy between cells or groups of cells. In the basis of the charge routing path (or direction of energy flow), active balancing circuits can be broadly classified as follows:

i. **Cell to cell** transfer where charge from a higher charged cell is transferred directly to a lower charged cell.

ii. **Single cell to pack** transfer where the excess charge of a higher charged cell is transferred to the whole battery pack, distributed among all component cells.

iii. **Pack to single cell** where the collective energy of the pack is transferred to a weak cell in the pack.

On the basis of circuit components and topology, active balancing circuits are found in literature to be of two types- circuits that use capacitive charge shuttling between cells and those that use dc-dc converters to transfer energy (hence charge) between cells. Some of the popular representative active balancing circuits are presented here along with a brief description of their operation and balancing methodology:

i. **Switched capacitor charge shuttling:** In this method capacitors are used to intermittently store charge and switches are used to route the change to and from the correct cell.

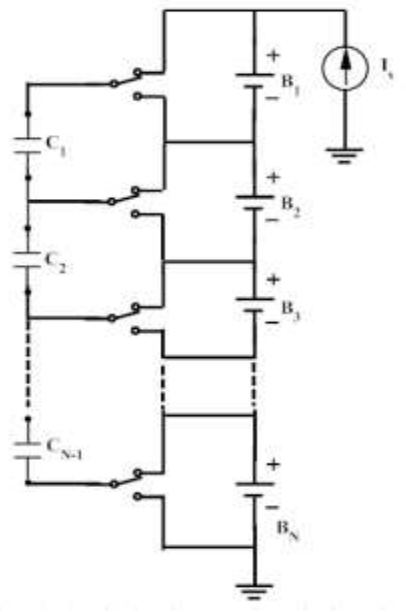

Figure 2.2 Switched capacitor shuttling. Source [4]

Each capacitor can transfer energy among its adjacent cells. Charge can be collected from a higher charged battery by connecting the capacitor across it using appropriate switching control. This charge can then by transferred to the adjacent lower charged battery by turning ON the appropriate switches. Since only adjacent cells can be affected by each capacitor, cells that are far away require time for charge transfer. This circuit has a high equalization time. A derivative of this circuit is shown below:

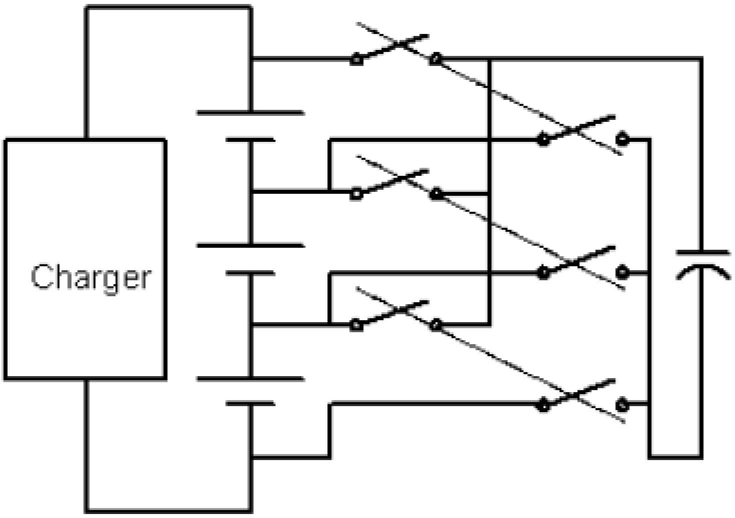

Figure 2.3 Single capacitor switched shuttling. Source [1]

This circuit requires only one capacitor to shuttle charges between any two cells. Reduction in capacitors comes at the cost of increased equalization time.

ii. **Multi-winding transformer based balancing:** In this circuit, each battery is connected to a winding which acts as the secondary winding. All these windings have the same primary which is connected to the battery pack via a switch. This topology is also called shared transformer circuit. The switch is normally closed and hence some energy is stored in the primary of the transformer. When a change in voltage or SOC is detected by the controller, the switch is turned off. The energy of the transformer primary is transferred to the cell with the lowest voltage. In this way, the energy of the pack is transferred to the weakest cell of battery pack. In a variation of this circuit, the structure is such that there is a switch at the secondary side of the multi-winding transformer instead of the primary. This switch is normally OFF. When a voltage difference is detected the switch corresponding to the highest charged cell is turned ON and the energy of that cell is transferred to the whole pack via the primary. The former structure is called flyback while the latter is called forward structure:

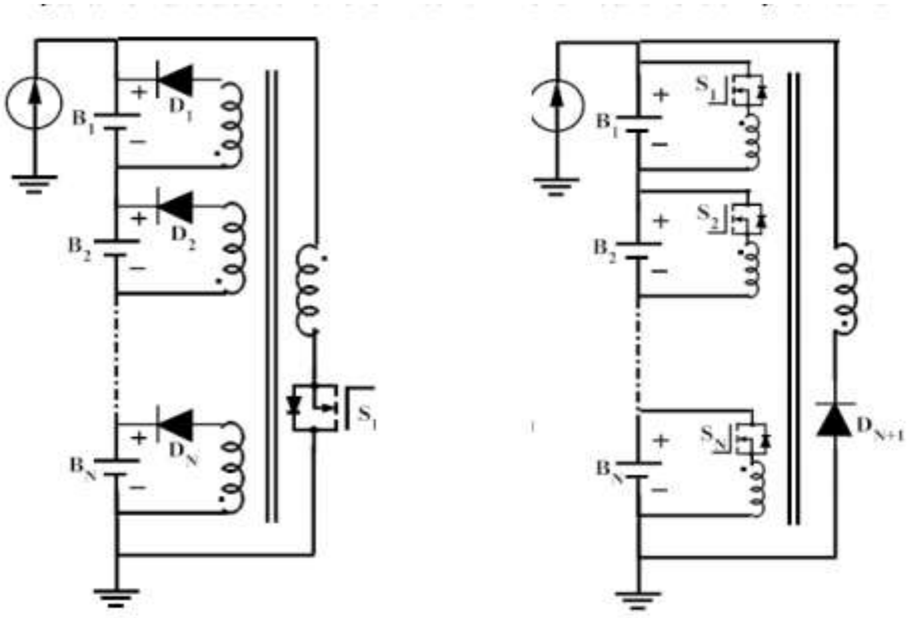

Figure 2.4 Multi-winding transformer based balancer[4]

This circuit has a complex circuitry and high cost due to the presence of multi-winding transformer.

iii. **DC-DC Converter based balancer:** In type of circuits, a dc-dc converter is connected to each battery and it acts as the Individual Cell Equalizer (ICE).

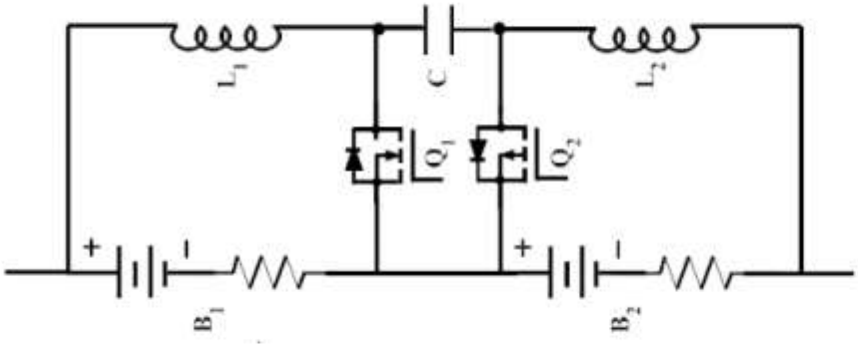

Figure 2.5 Cuk converter based battery equalizer[8]

The dc-dc converter converters are able to transfer energy between adjacent cells only. As a result, these circuits have a long equalization time. The circuit has variants based on the type of converter used as ICE. These are generally Cuk converters, Buck/Boost converters and Flyback converters, Quasi-resonant converters etc.

iv. **Buck Boost converter based battery balancer (Inductive charge shuttling):** In this circuit, either end of each cell is connected to each end of a single inductor via two unidirectional paths. The inductor shuttles charge between any two batteries. The operation of equalization is similar to the operation of a buck boost converter. Because of high balancing currents this circuit has smaller equalization time. The analysis of this circuit is the subject of this dissertation and is covered in detail in the next chapter.

In this chapter, a general introduction to battery operated systems was presented. The quantities used to define and assess battery parameters were covered. A discussion of various challenges faced in working with batteries along with how those challenges contribute to the problem of battery cell imbalance was presented. Additionally, the need for battery balancing was justified. This chapter concluded with a review of battery balancing circuits found in literature. The next chapter explains the buck boost converter based battery balancing circuit in detail.

CHAPTER 3: BUCK BOOST CONVERTER BASED BATTERY CHARGE BALANCING CIRCUIT

In the last chapter, we covered definitions of quantities used to compare and assess batteries along with the many challenges faced in battery operation. We gave a brief introduction of various passive and active battery balancing circuits. In this chapter, the buck boost converter based battery balancing circuit is given a more rigorous treatment. We will cover the circuit design, component selection and circuit operation.

3.1 Circuit Design

In this section we cover the design of the circuit and the connections between components. This method is a cell to cell charge transfer type battery balancing method. The basic principle of balancing of this circuit is to achieve controlled charge transfer from a higher charged to lower charged battery via an inductor. The circuit effectively implements “inductive” charge shuttling. The inductor shuttles charge between any two batteries. The operation of equalization is similar to the operation of a buck boost converter.

The circuit diagram of the converter is shown in Fig 3.1. In this circuit, either end of each cell is connected to each end of a single inductor L via two unidirectional paths. Each unidirectional path consists of a switch and a diode. By controlling these switches, charge can be routed to and from any particular battery to the inductor.

In the proposed battery equalizer, the charge of a battery moves to another battery in a one-to-one operation. For example, if battery B1 is fully charged and battery B2 is the weakest charged, switch S1d and S1d2c is turned on and the current of inductor L is built up. After that, switch S1d is turned off and switch S3d2c is turned on. The stored energy in L will be delivered to battery B2. Consequently, the charge of the fully charged battery B1 transfers to the weakest charged battery B2. The detailed analysis is presented in next Section.

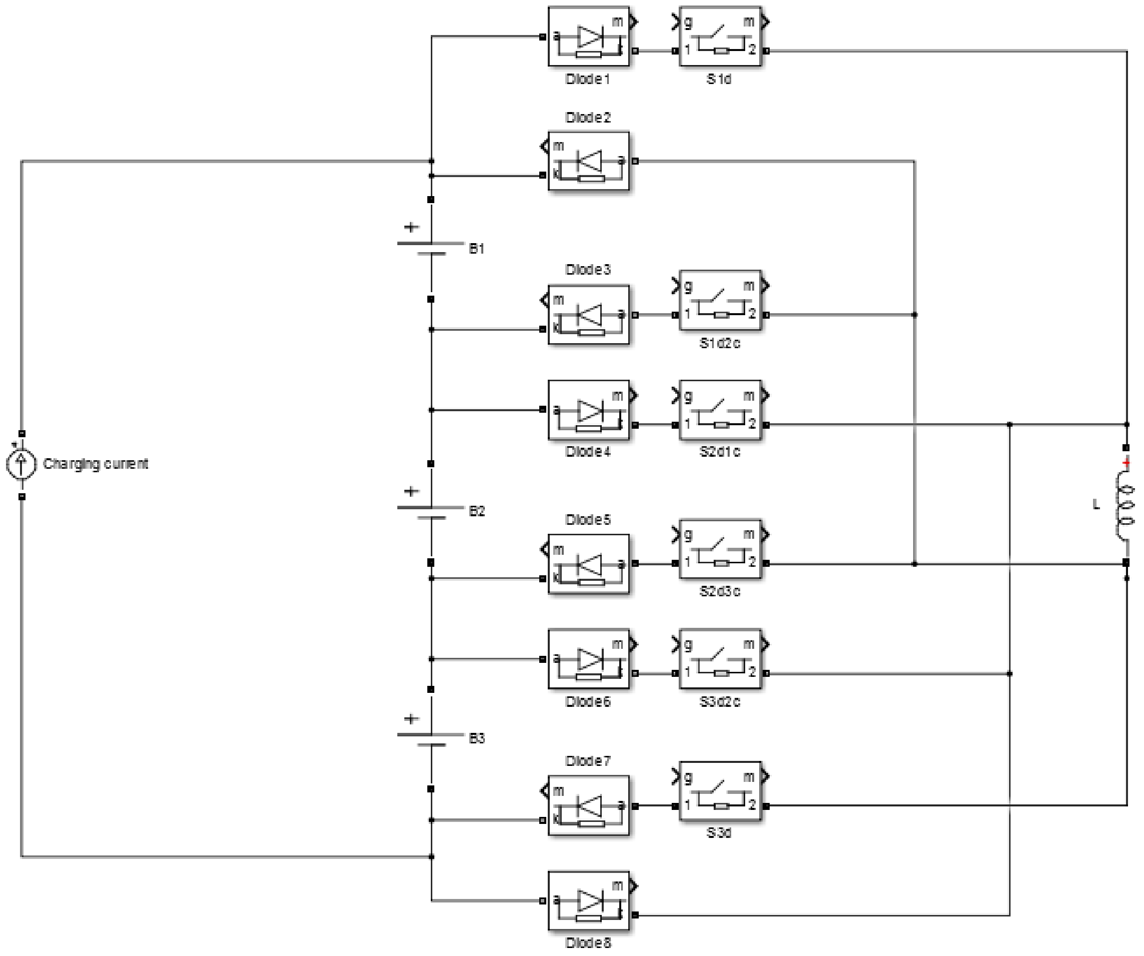

Figure 3.1 Buck Boost converter based battery balancing circuit

3.2 Circuit Operation

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

1. All switches are ideal.

2. All diodes are ideal and no voltage drop exists.

In the proposed battery equalizer, the equalization process is achieved by transferring equalization current. The equalization current is extracted from a fully charged battery and the current flows to the weakest charged battery. To make this operation, voltage/SOC sensing circuits are needed to each battery. The main operation consists of two modes occurring back to back.

Before describing the analysis, it is assumed that the battery B1 is fully charged and battery B2 is the weakest charged. In this case, the charge or energy flows from battery B1 to battery B2. The current paths of this case are shown in Fig. 3.2 and Fig 3.3. The equivalent circuit is similar to the buck-boost DC-DC converter. The operation is also similar to the buck-boost DCM operation.

The modes of operation are explained as follows:

Mode 1: The charge is extracted from battery B1. Switches S1d and S1d2c are turned on and these switches are in the discharging path of battery B1. And then, the current in inductor L is built up. The terminal voltage of battery B1 is applied to L. According to the assumption, the current of inductor or discharging B1 is built up with constant slope Equation (3.1). Equation (3.2) indicates the maximum current of mode 1.

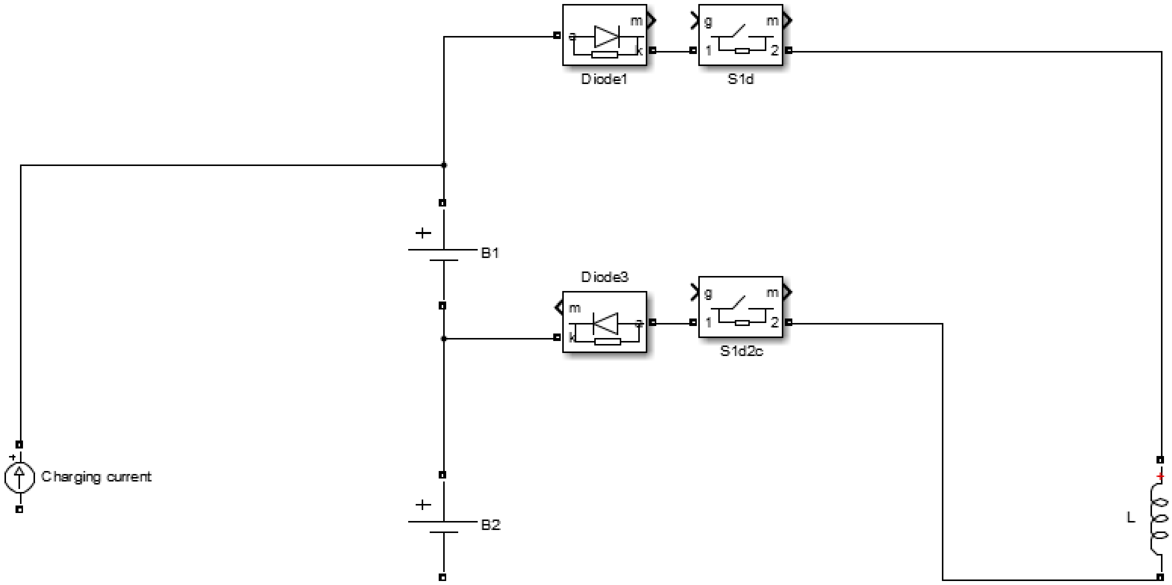

Figure 3.2 Mode 1: B1 Discharging

Equation (3.1)

$$i_L(t) = \frac{V_{B1}\times t}{L}$$

Equation (3.2)

$$i_{peak} = \frac{V_{B1}\times DT_s}{L}$$

During mode 1, the equalizer circuitry transfers the energy of battery B1 to inductor L. Equation (3.3) shows the whole transferred charge.

Equation (3.3)

$$Q_{dis} = \frac{1}{2}\times DT_s \times ipeak \ = \frac{1}{2}\times \frac{V_{B1}}{L}\times (DT_s)^2$$

Mode 2: When switch S1d is turned off and switch S3d2c is turned on, mode 2 starts. Consequently, the switches in the charging path of battery B2 are turned on such as switch S1d2c and S3d2c. In this mode, the energy stored in inductor L flows to battery B2. The terminal voltage of battery B2 is applied to inductor L in reverse. The current of inductor decreases with constant slope.

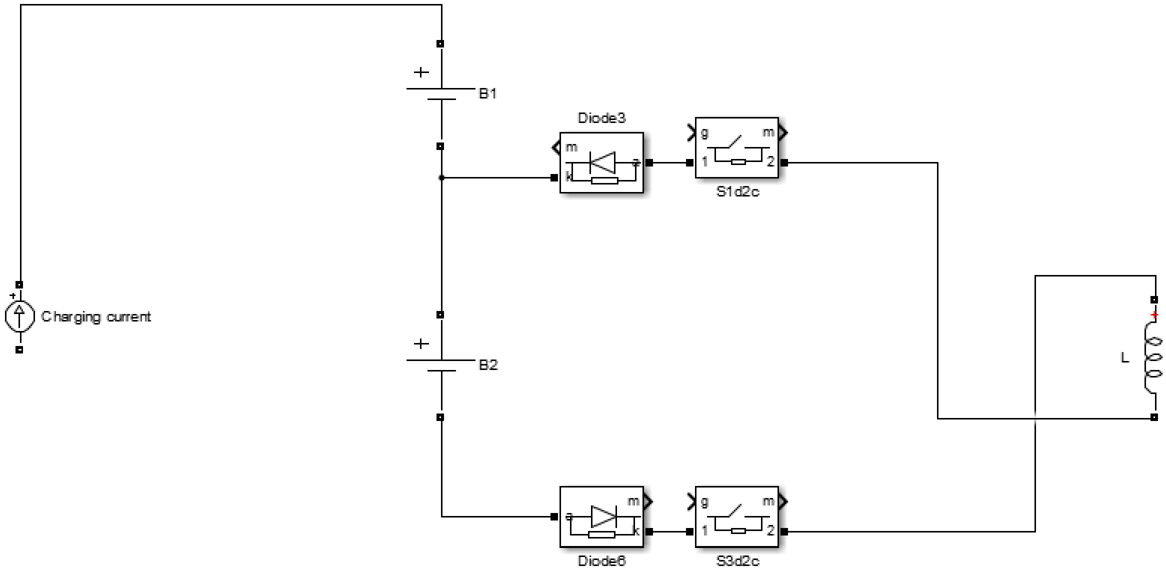

Figure 3.3 Mode 2: B2 Charging

Equation (3.4)

$$\boldsymbol{i_L(t) = \frac{V_{B_1} \times DT_s}{L} - \frac{V_{B_2} \times t}{L}}$$

Q (charge) transferred to B_2 is the same as discharge from B_1 and is given by equation 3.3 above.

As explained in this section, we see that as long as all switches are off, the circuit merely charges the batteries in series. When battery B1 is at a higher SOC compared to battery B2, charge from B1 is transferred to B2 in two modes. The charge is routed through the inductor by appropriate switching control. The time for which the switches are ON should be small enough to ensure that the inductor does not elicit a current high enough to get saturated. In addition to that, current through the inductor should be discontinuous otherwise residual energy will keep building up in the inductor. The expected waveforms are as follows:

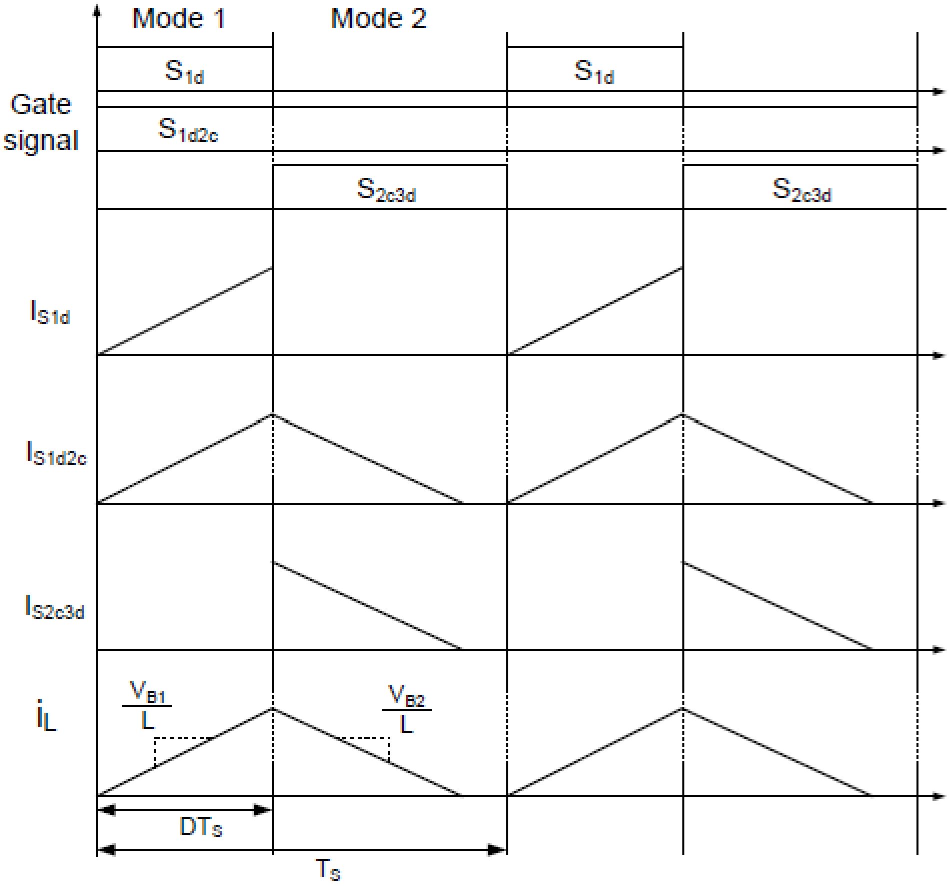

Figure 3.4 Current Waveform during equalization process

3.3 Design Considerations

In charging process, the whole charging current I_S flows through the battery pack constantly. And the proposed equalizer transfers the charge of batteries through one inductor L. As explained in the previous section, during equalization, the charge that is transferred to the inductor during mode 1 must be completely transferred to another battery in mode 2 before the end of the switching time period. In other words, ((1-D) *Ts) must be sufficient to allow all the charge accumulated in the inductor during D*Ts. Even for the smallest voltage difference between batteries, this must be true. Therefore $D < 0.5$ ensures this always.

Even during the equalizing process, the batteries are still getting charged with the charging current. This current adds charge to both the batteries, irrespective of the charge extracted or added by the inductor. When two or more battery cells are fully charged at once, each must be utilized to charge the weaker batteries in the pack, that is to say they must be discharged by turns in the equalizing process to avoid overcharging. For this, the total discharging of the battery in one switching cycle must be greater than the charge that it will receive until it is discharged through the inductor again.

Consider a series connected battery stack with n battery cells. In the extreme case if (n-1) battery cells are fully charged and their voltage at full charge is V_{B_1} except for only one battery, the condition to avoid overcharging is

Equation (3.5)

$$\boldsymbol{\frac{1}{2} \times DT_s \times ipeak \geq (\mathbf{n} - 1) \times I_{charging} T_S}$$

Using the expression for i_{peak} from equation 3.2, we obtain a constraint relation between the inductance L, duty cycle D, the charging time T_s and the charging current $I_{charging}$.

Equation (3.6)

$$L \leq \frac{V_{B_1} \boldsymbol{D^2 T_S}}{\boldsymbol{2(n-1) I_{charging}}}$$

Using these guidelines the circuit parameters and switching variables can be finalized. This will be shown in the sections that follow.

3.4 Control Algorithm

In this section the development of the control algorithm is presented. Let us assume for simplicity that only 2 batteries connected in series are involved in the circuit. During the charging of batteries, equalization process is triggered when a significant change in SOC levels is detected by the corresponding sensor circuits. The equalization process should start at the appropriate time without interrupting the charging process constantly. A threshold value is selected close to the desired value of the final SOC. Both batteries are charged by the same charging current and all switches are OFF until one of the SOCs reaches the threshold SOC selected. After this point, the circuit begins equalizing the batteries by routing charge from the higher charged to the lower charged battery by controlling the corresponding set of switches.

The feedback of the charging process could be either voltage based or SOC based. To estimate the SOCs of the batteries, the initial value of SOC is deduced from the open circuit voltage when the circuit is off. From this point onwards, a current sensor placed in series with the battery can be used to measure the charging/discharging current and then integrating it with time to find the net charged received by the battery. This method is called Coulomb Counting. Alternatively, choosing simplicity and economy at the expense of preciseness, voltage sensors may be used to measure the terminal voltages to estimate the SOCs from the charge/discharge characteristics at the corresponding current. In this section, a voltage measurement based algorithm is presented.

All batteries have a non-zero response time with respect to changes in charging current. Measurement of terminal voltages when a pulsating current is flowing through it can be a misleading indicator. In order to make reliable measurements of terminal voltages and currents through the circuit some amount of time must be allowed to pass until the voltages are stabilized at a constant current. During this time, all switches are turned OFF and the batteries are merely being charged by the charging current from the source. The dead time also allows for the higher charged battery to recover charge that was lost in the preceding equalization stage. The operation of the circuit is thus like a state machine switching between equalizing state and dead state. Time has to be allotted for equalizing as well as stabilizing. Let the time allotted to the equalizing phase be t_{eq} and the time allotted to the dead phase be t_{dead}. Keeping all these considerations in mind, the control algorithm is developed as follows:

Terminal Voltage feedback based control algorithm

1. Start.

2. Charge circuit at constant current from the source.

3. If any battery has reached $SOC_{threshold}$ go to 4.

4. Initialize time t=0.

5. While $t < t_{eq}$

In equalizing phase (Charge is transferred from one battery to another).

6. End of equalising phase . Set t = 0.

7. While $t < t_{dead}$

In dead phase (all switches turned off, constant current charging)

8. End of dead phase. Stopping criteria:

If voltage (or SOC) difference is within desired range, go to 9, else go to 4.

9. Stop charging.

The algorithm is represented in the form of a flow chart.

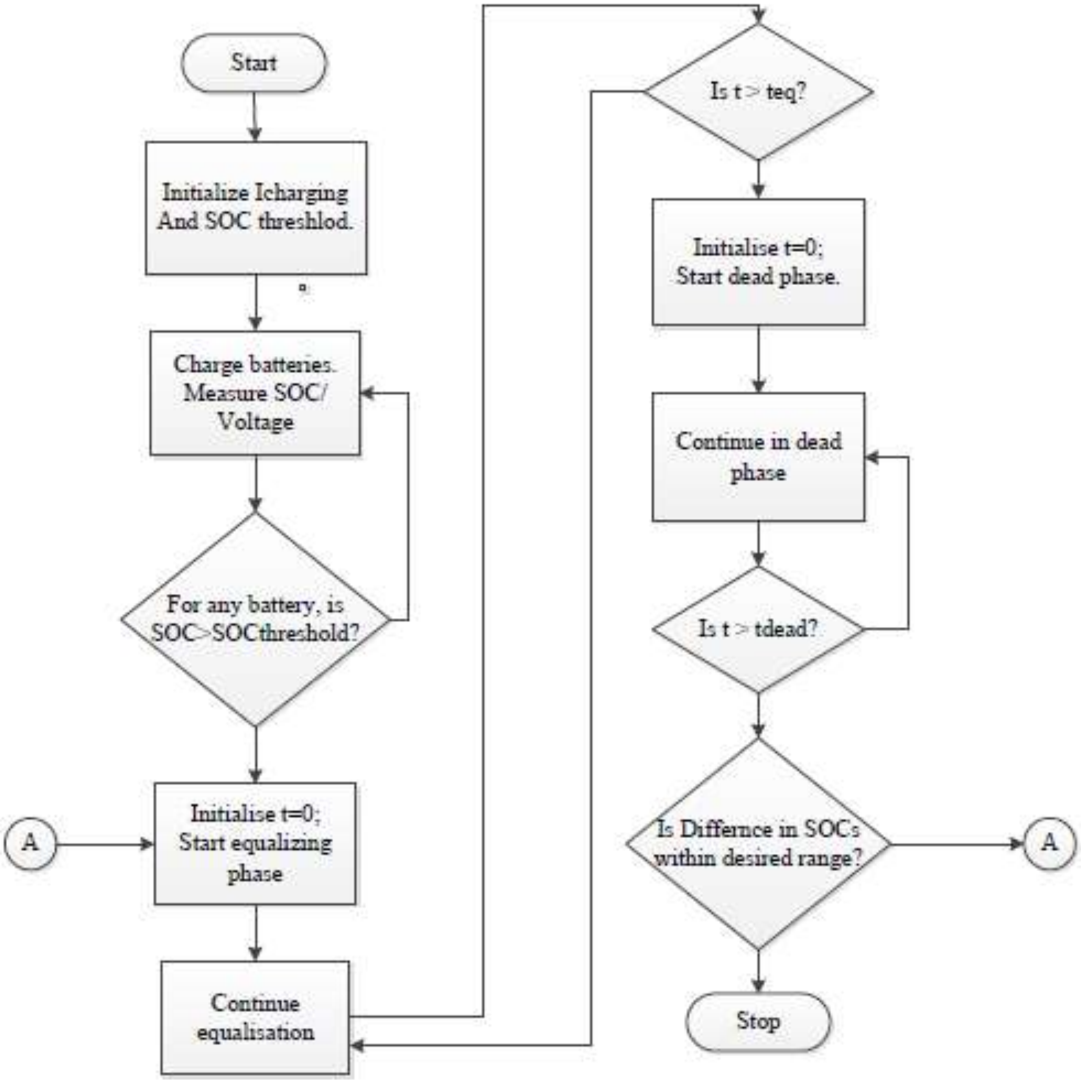

Figure 3.5 Balancing Algorithm of the circuit

In this chapter, the buck boost converter based balancing circuit was introduced. The circuit topology, operation and design parameters were explained in detail. The control algorithm for running the state machine circuit was also covered. In the next chapter, the circuited has been simulated to test design parameters and analyze the circuit operation under various input conditions.

CHAPTER 4: SIMULATION

In the previous chapter the theory of operation of the balancer circuit was covered in great detail. Using the design guidelines presented in the previous chapter, the circuit is simulated. In this chapter the results of the simulation of the circuit and their inferences are presented.

4.1 MATLAB Simulation

The balancer circuit was simulated in MATLAB to supplement the theoretical analysis of circuit operation. Model parameters had to be selected in order to appropriate results. For the sake of simplicity and obtaining a basic proof of concept, the circuit is simulated for a system of two batteries connected in series and being charged by a constant current source. The process of determining model parameters is presented here.

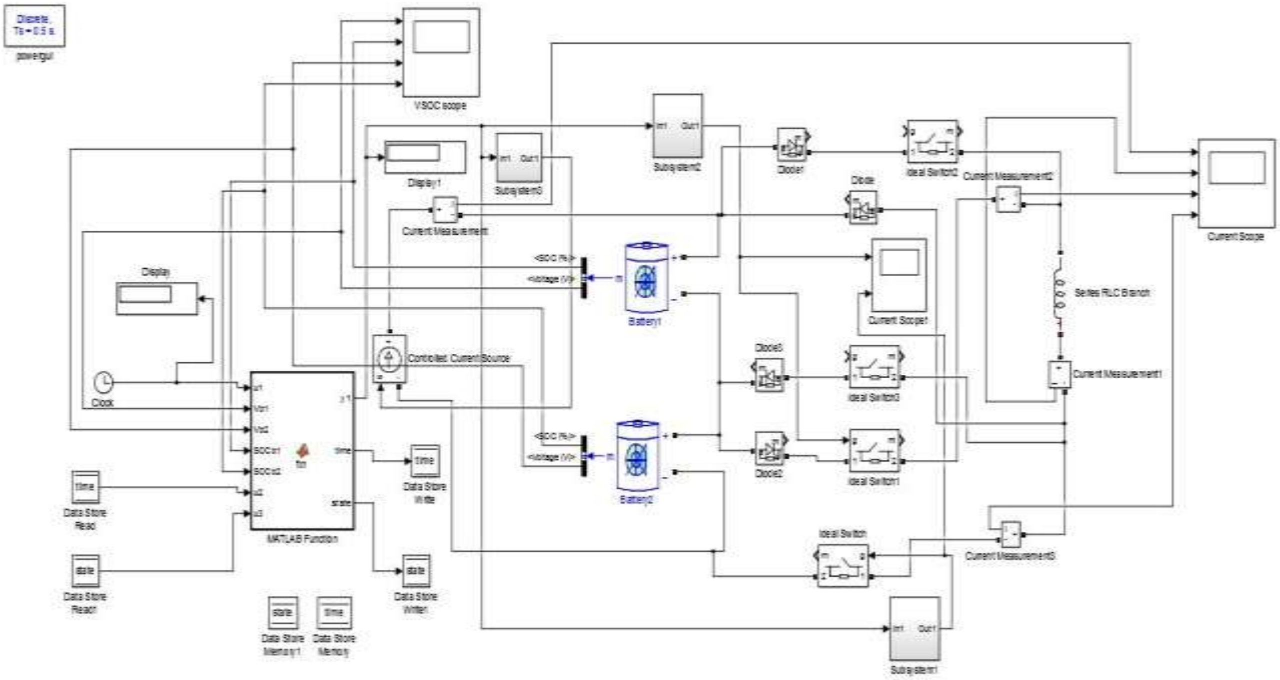

Figure 4.1MATLAB Simulink Model

Model Parameters:

- Batteries chemistry: Lead acid
- Rated capacity: 4Ah
- Nominal Voltage: 12V

The discharge (or charge) characteristics for this battery are generated by the MATLAB model.

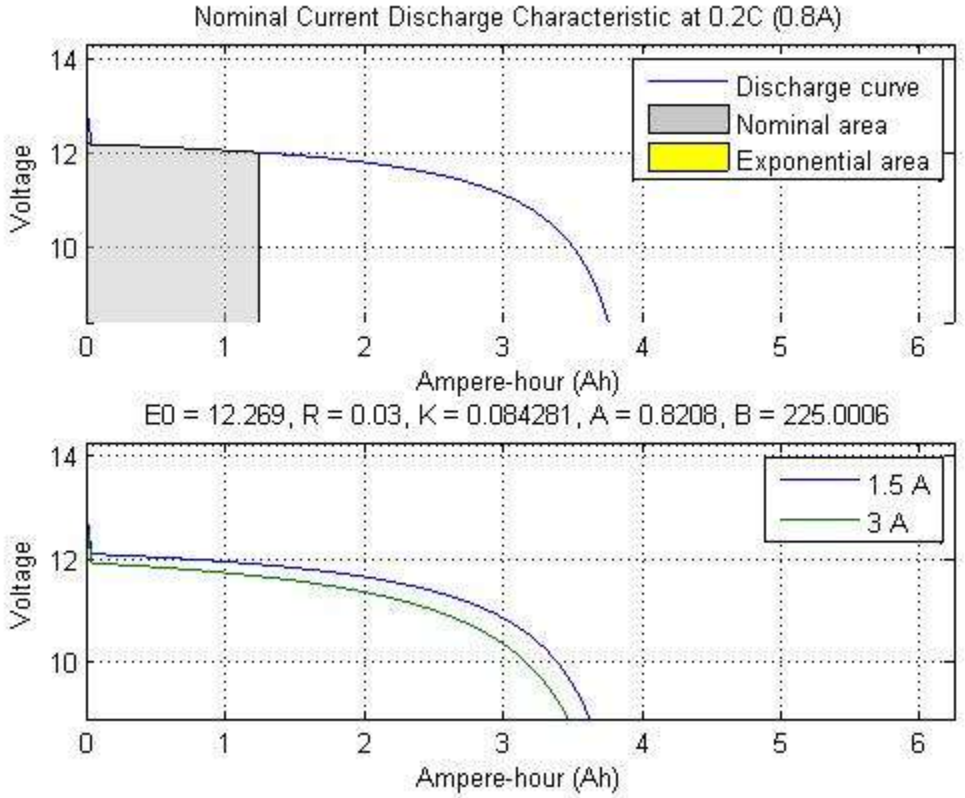

Figure 4.2 Basic discharge characteristics for a lead acid battery

- The value of D is selected such that we maintain discontinuous mode of operation during equalizing phase. D =0.4 (40% duty cycle).
- Value of L can be chosen according to the equation (3.6)

$$L \leq \frac{V_{B_1} D^2 T_S}{2(n-1) I_{charging}}$$

Where n=2 for 2 batteries.

With the inclusion of a dead phase, care must be taken that the higher charged battery does not get overcharged during the dead phase. Since we are implementing the algorithm developed in the previous chapter, we must implement the state machine for equalization phase and dead phase. Since we need to provide a dead phase to measure a reliable value of terminal voltages, the charge gained by both batteries in the dead phase needs to be accounted for. If inductance is chosen in such a manner that charge lost by the higher charged battery in the equalization phase equals the charge it gains during the dead phase then the equalization and dead phase together have no effect on the SOC of the higher charged battery over time. This allows setting SOC threshold to be very close to the final desired (charged) SOCs at the end of entire charging process.

Ideally value of L must be set such that:

net discharge for the higher charged battery during equalizing phase = net charge during dead phase.

This ensures that the SOC of the higher charged battery remains constant while the lower charged battery catches up i.e

Equation (4.1)

$$\frac{1}{2} \times Dt_{eq} \times ipeak - I_{charging}t_{eq} = I_{charging}t_{dead}$$

Where

$$i_{peak}(t) = \frac{V_{B_1} \times DT_s}{L}$$

This gives us:

Equation (4.2)

$$L = \frac{1}{2} \times \frac{V_{B_1} D^2 t_{eq}}{I_{charging}(t_{eq} + t_{dead})} \times T_s$$

The circuit needs to be simulated for upto 30 min to see complete charging process for a practical rating of lead acid battery. As a result of heavy computation, the simulation time for a regular, continuous solver is very high (> 24 hrs). To reduce simulation time in MATLAB the discrete solver is used with step time 0.05 s.

This forces us to keep the switching time period to a minimum of 1 s and hence value of L used in the simulation is unusually high (in H). However these adjustments are only made for simulation purposes. Moreover, as seen in the equations above T_s and L can be reduced in the same ratio without bringing any change to the charging time and net charge transfer.

- $T_s = 1s$
- L = 220 mH
- SOC desired at end of charge = 80-85%

Lead acid batteries have a response time of about 30- 40 seconds. Accordingly t_{dead}=2 min is used to provide sufficient time for battery parameters to stabilize.

4.2 Results and Inferences

In this section the results of the simulation for a variety of input conditions are presented. To demonstrate the behavior of the circuit, simulation results for different initial values of batteries SOC are shown here.

i. Case I

- Battery1 initial SOC = 50%
- Battery 2 initial SOC = 70%
- Balancing circuit is not used

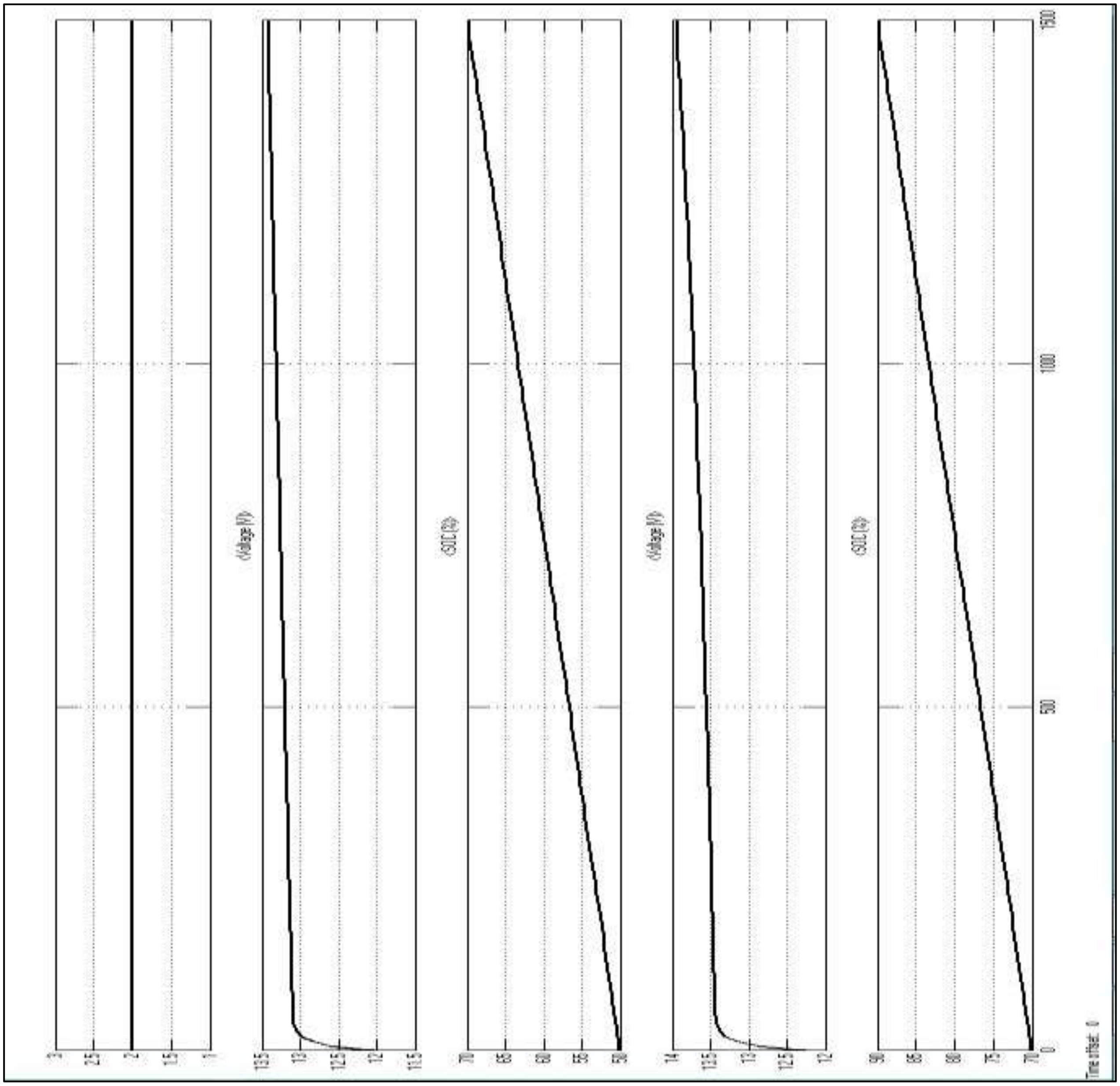

Figure 4.3 Results for case I

These are the results for the system without the balancer circuit. It can be seen that the initial 20% difference in SOC continues to the very end. While one battery has reached 90% SOC the other battery is still at 70%. Charging the second battery at this stage is highly undesirable as the battery can get overcharged. Charging process has to be halted even though other battery is still undercharged.

ii. Case II

- Battery1 initial SOC = 50%
- Battery 2 initial SOC = 70%
- Teq= 2 min

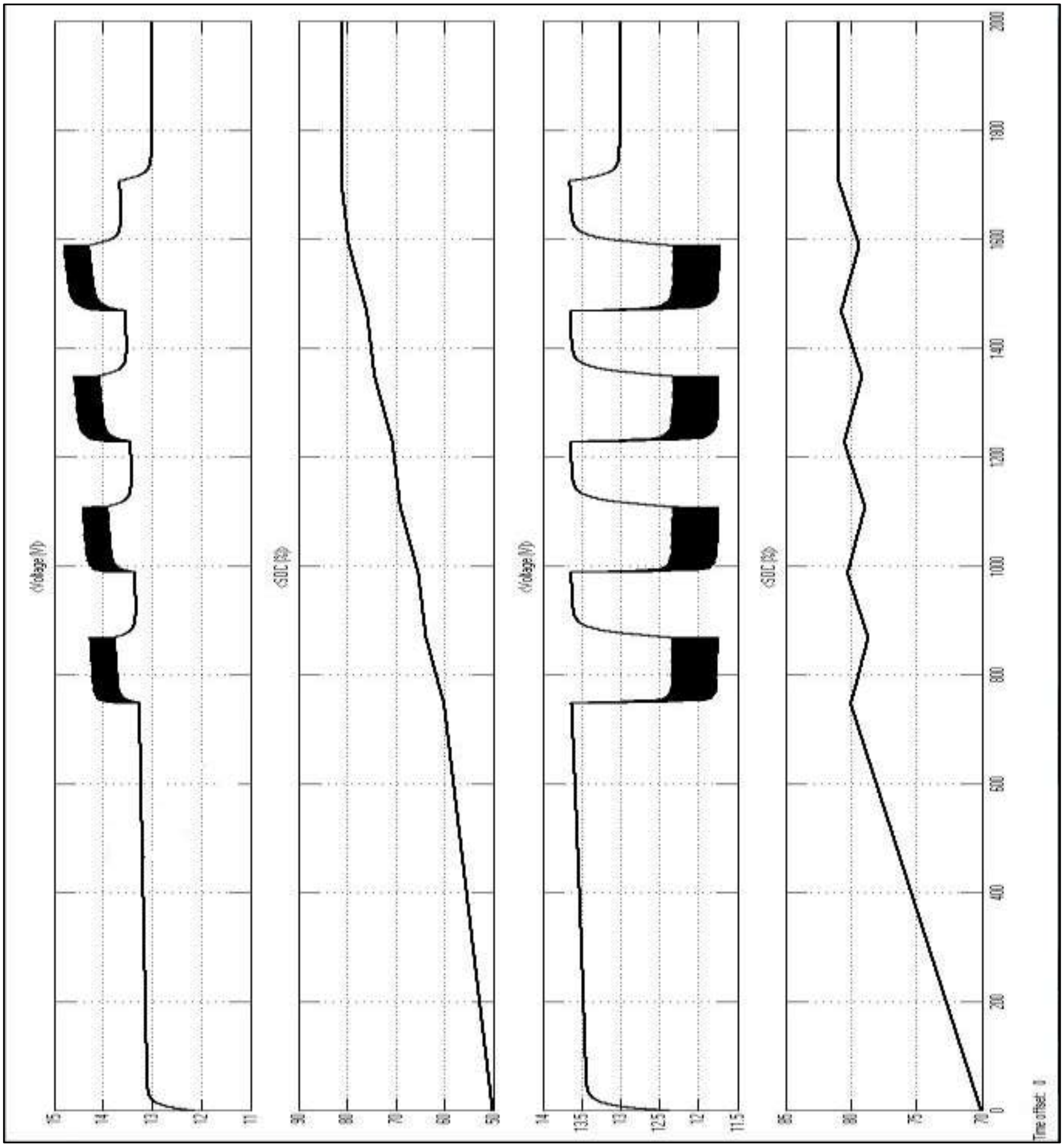

Figure 4.4 Results for case II

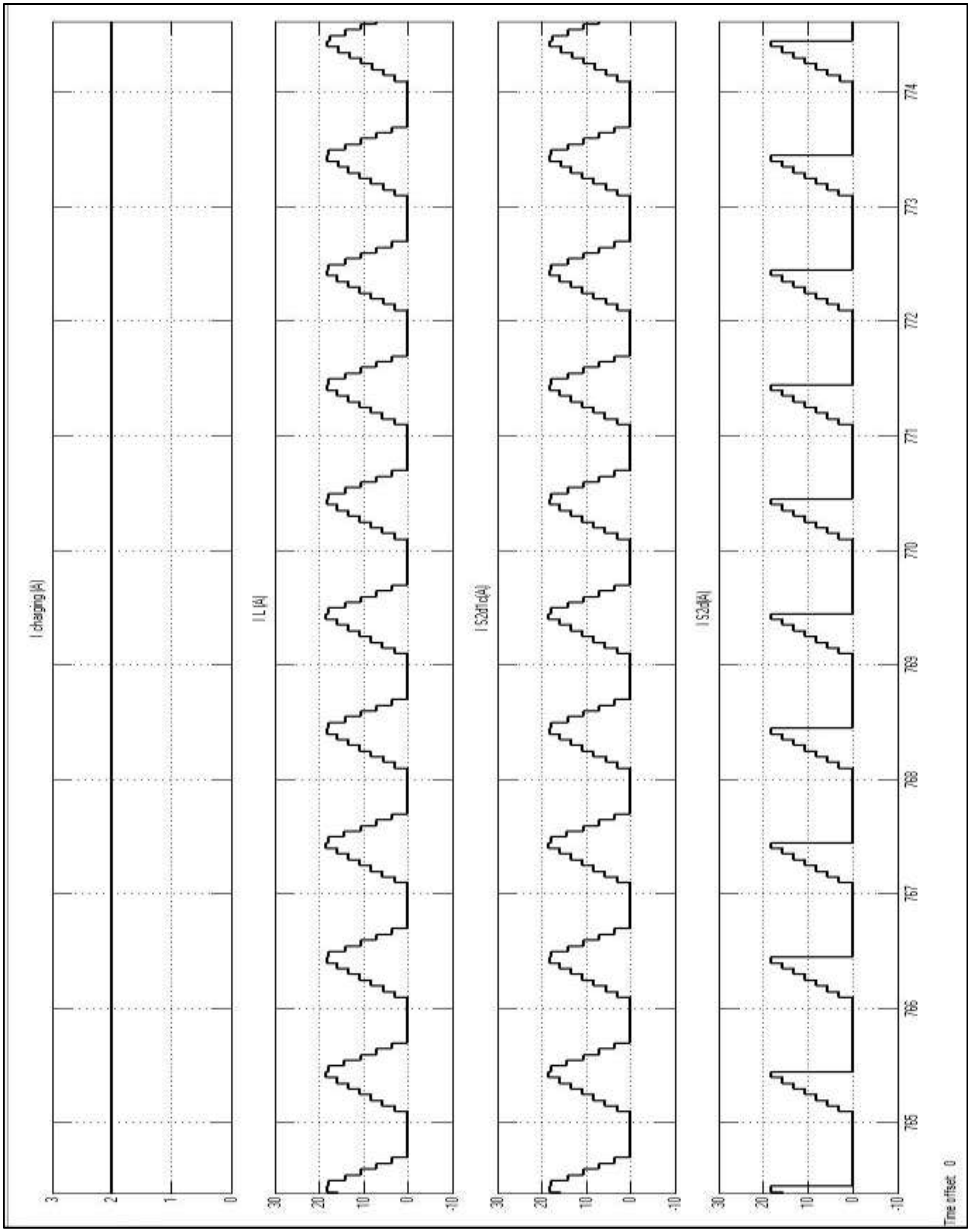

Figure 4.5 Current waveforms during equalization

As seen by the voltage and SOC waveforms on Page22, equalization begins when one battery reaches 80% SOC and after 4 equalisation cycles, the SOCs are within 2% and voltages are within 0.05V.

iii. Case III

- Battery1 initial SOC = 50%
- Battery 2 initial SOC = 70%
- Teq= 1 min. Results below show the increase in equalization cycles as well as total charging time due to smaller $t_{eq.}$

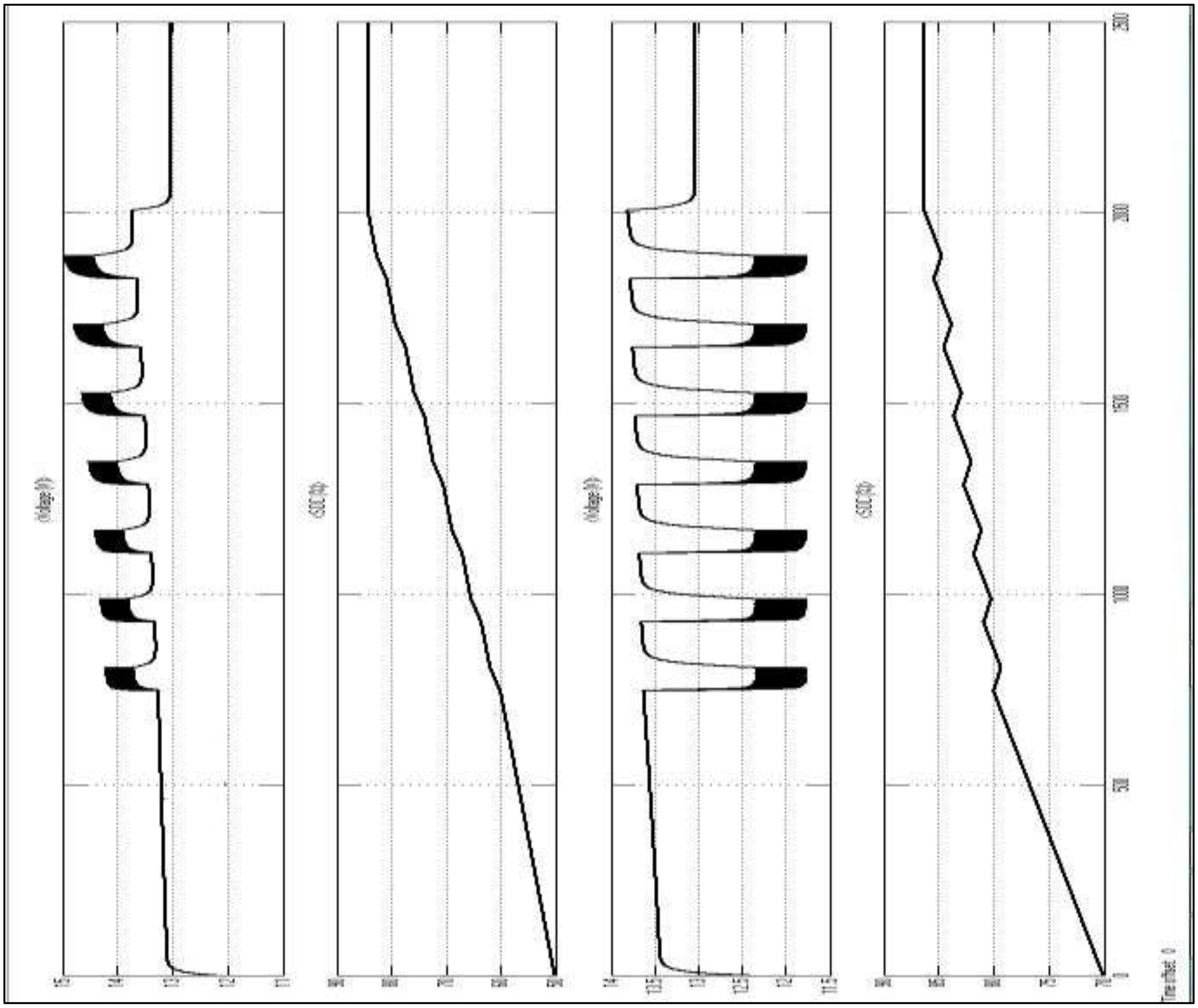

Figure 4.6 Results for case III

iv. Case IV

- Battery1 initial SOC = 50%
- Battery 2 initial SOC = 80%

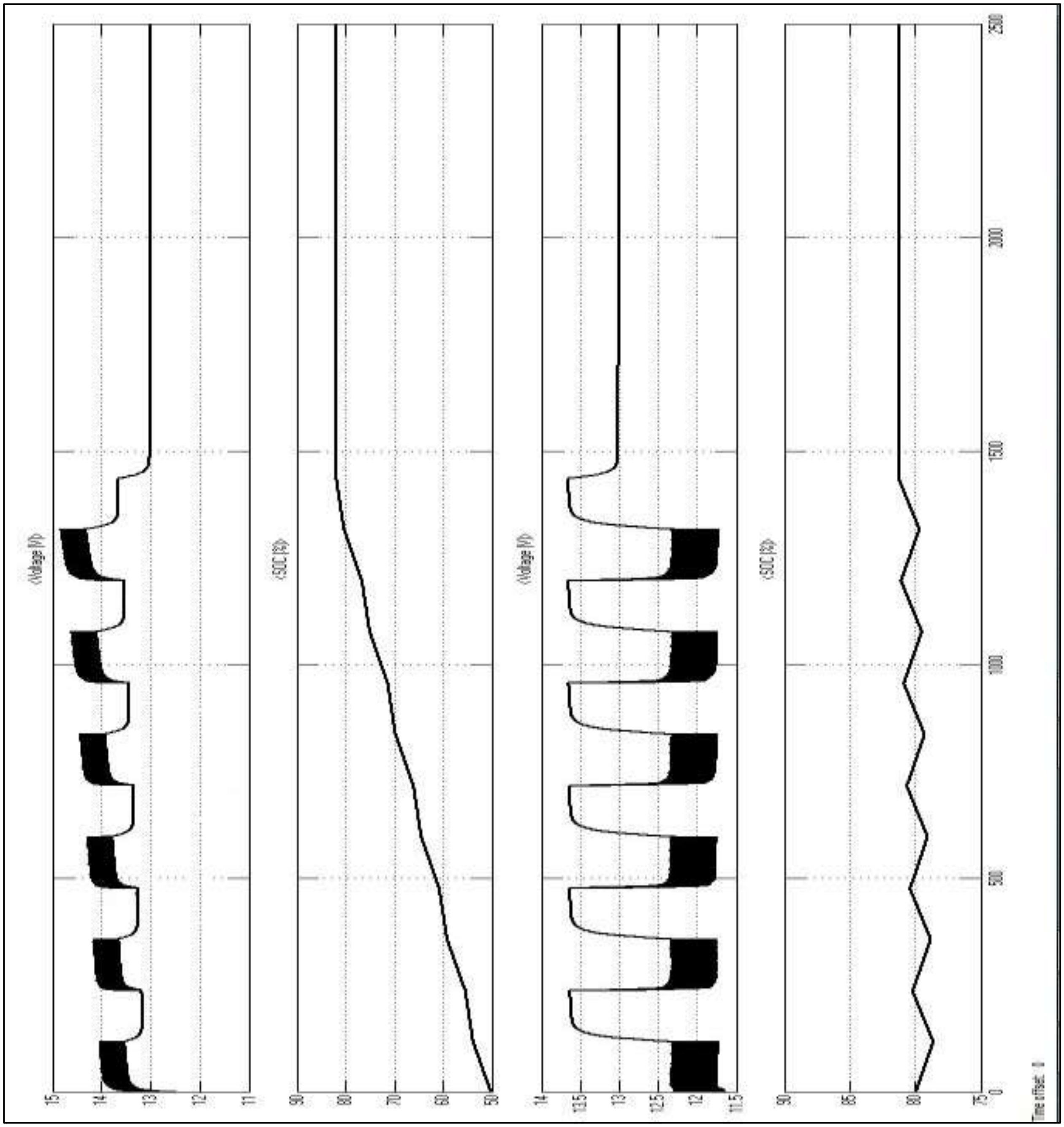

Figure 4.7 Results for case IV

v. Case V

- D=0.3, for the same value of remaining circuit parameters.
- Battery1 initial SOC = 50%
- Battery 2 initial SOC = 70%
- Teq= 2 min

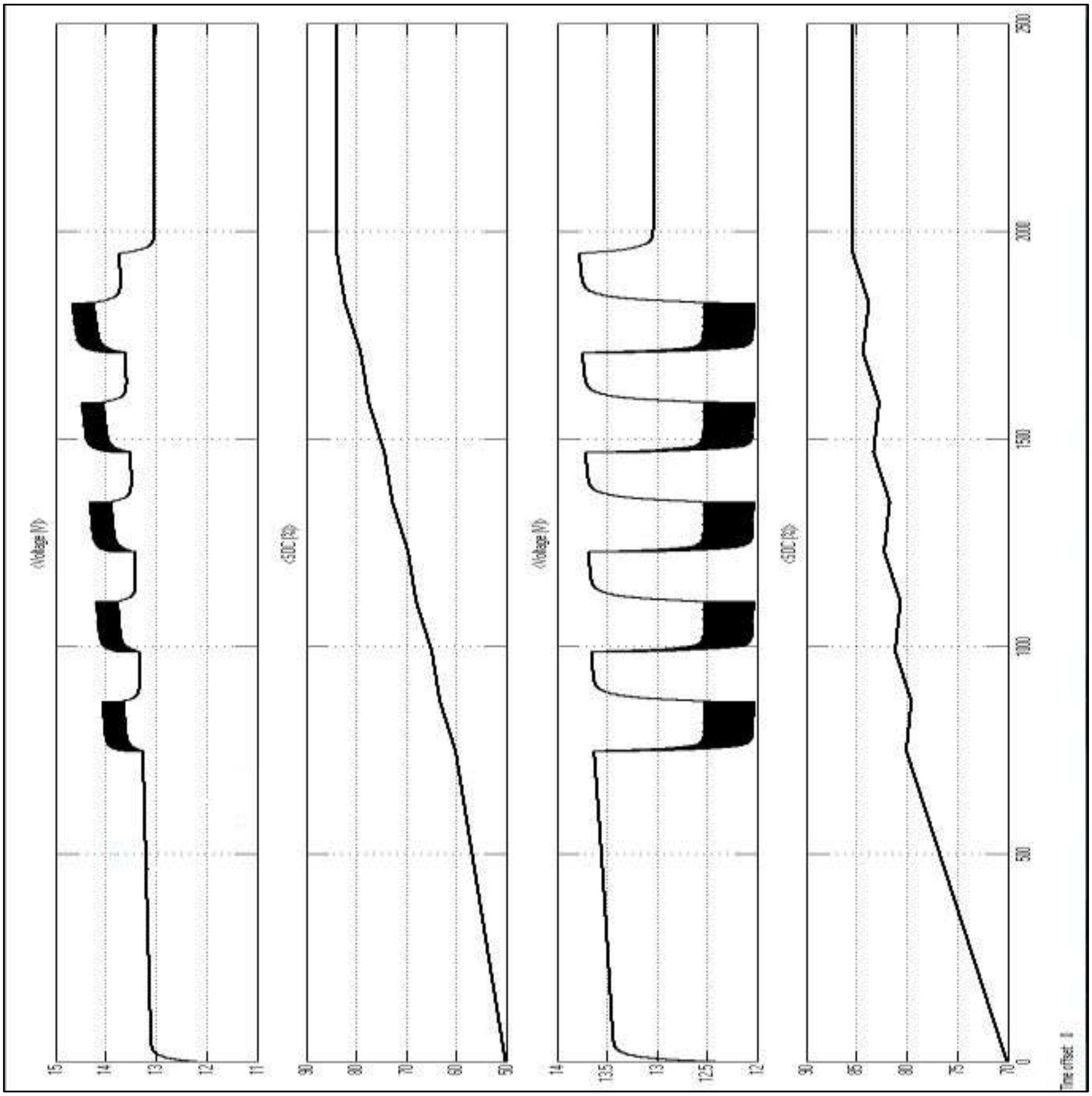

Figure 4.8 Results for case V with D = 30%

As seen in the voltage and SOC waveforms, the amount of discharge from battery2 is reduced because of a smaller duty cycle for the same inductor value. As a result, it takes more equalizing cycles and more time to balance.

Current waveforms are shown below.

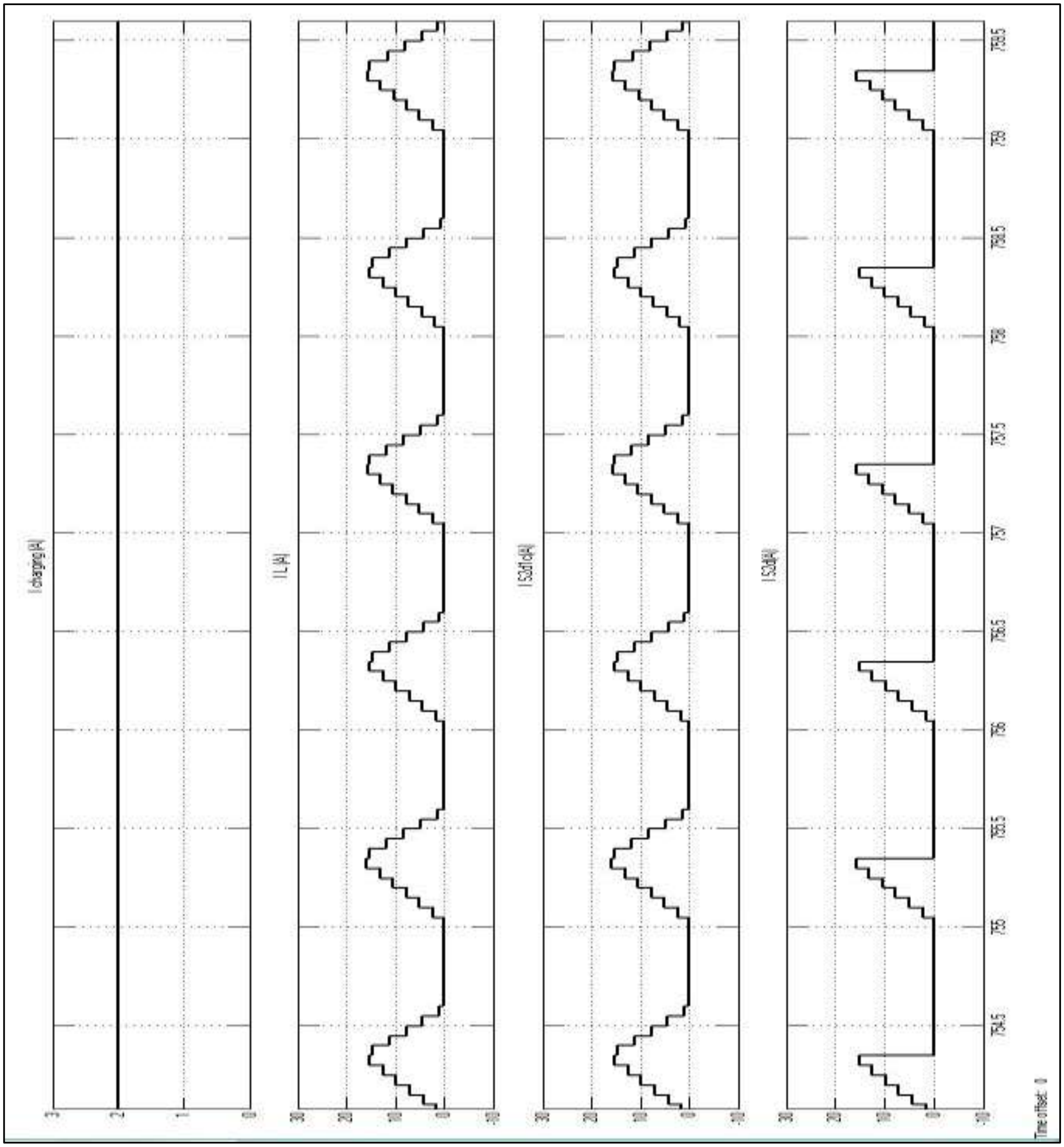

Figure 4.9 Current waveforms for D=30%

The results show the functionality of the battery balancer circuit. The simulation verifies the theoretical analysis presented in the previous chapter. Two batteries having a large difference in the initial SOCs, converge close to the same SOC towards the end of charging. In the next chapter, the hardware realization of the battery balancer circuit and other related documentation is presented.

CHAPTER 5: HARDWARE CIRCUIT DEVELOPMENT

In the last chapter, battery balancer circuit was modeled to verify the operation of the circuit under different input conditions. In this chapter, the development of hardware prototype of the circuit is presented. A description of every component used to realize the power and control part of the circuit is covered here along with the results and inferences.

5.1 Hardware Setup

A buck boost converter based battery balancing circuit was realized using switches, sensing circuits and a controller. The developed circuit had a provision to balance three series connected batteries. Lead acid batteries were used, since they are easier to handle, cheaply available and not too sensitive to operating conditions. The unidirectional paths between battery terminals and inductor were realized by using power MOSFETs in series with power diodes. To determine the state of charge for each battery, current sensing circuits were used in series with each battery. The system was charged with a constant dc current supply. Lastly, the control algorithm and gate signals for switches were generated using a microcontroller. Each of the components of the setup is described in the following sections along with their specifications.

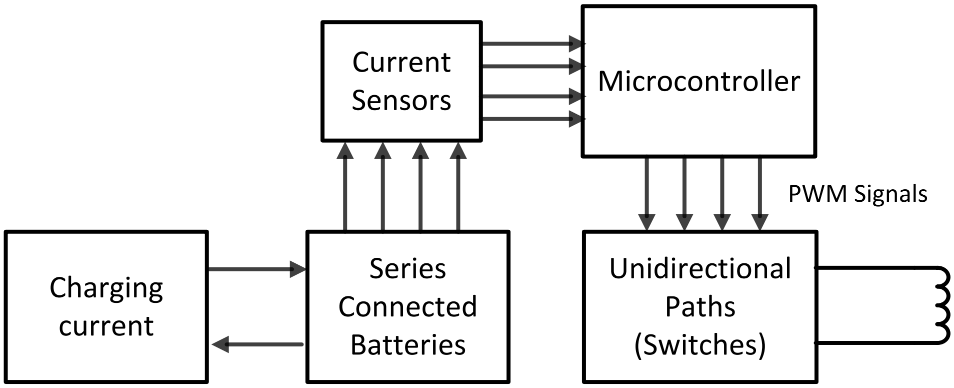

Figure 5.1 Block diagram of hardware setup

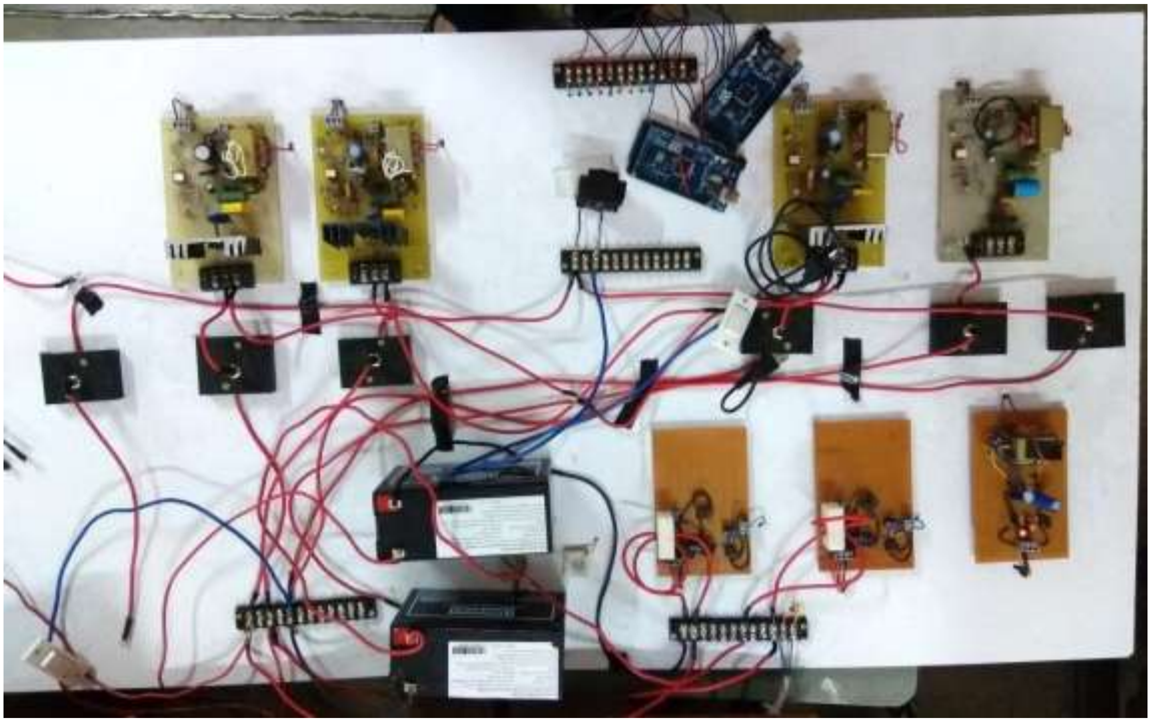

Figure 5.2 Image of the Hardware setup

5.1.1 Batteries

Lead acid batteries were used in the circuit to demonstrate the balancing operation of the circuit. While the circuit may be used for batteries of any chemistry, lead acid batteries are cheap, safe and easy to handle as well as robust enough to handle small amount of mal operation. The specifications of the batteries are as follows

- Nominal Voltage = 12V
- Capacity 7.2 Ah at 20 Hr

Figure 5.3 Image of the battery used in the circuit

5.1.2 Switches

6 switches were developed for the balancer circuit. The unidirectional paths from battery terminals to inductor are realized using power MOSFETs and power diodes. The MOSFET used in this circuit is IRFP460. The specifications of the MOSFET are as follows:

- Maximum drain source current: 20A
- Maximum drain source voltage : 500V
- Drain source resistance : 0.27 ohm

A power diode rated 16A is used in every unidirectional current path.

The pulse amplification and isolations circuit forms the MOSFET gate driver circuit.

5.1.3 Pulse Amplification and Isolation Circuit

Power MOSFETs used in the circuit require a gate source switching signal of 12V. However the control circuit generally generates a low voltage signal (5V in this particular case). Thus, pulse amplification and isolation circuits are required. The optocoupler MCT2E is used to isolate the high voltage power circuit from the low voltage control circuit. As shown in the figure, the input transistor conducts when current flows through the base from the 5V switching signal. When this signal is high, the input transistor goes into saturation and LED of the optocoupler glows. The photo transistor in the MCT2E thus saturates and connects the base directly to the emitter of the output transistor. The output transistor goes into cut- off and this allows the gate terminal to pull up to 12 V. The input and output transistors used in this circuit are 2N2222.

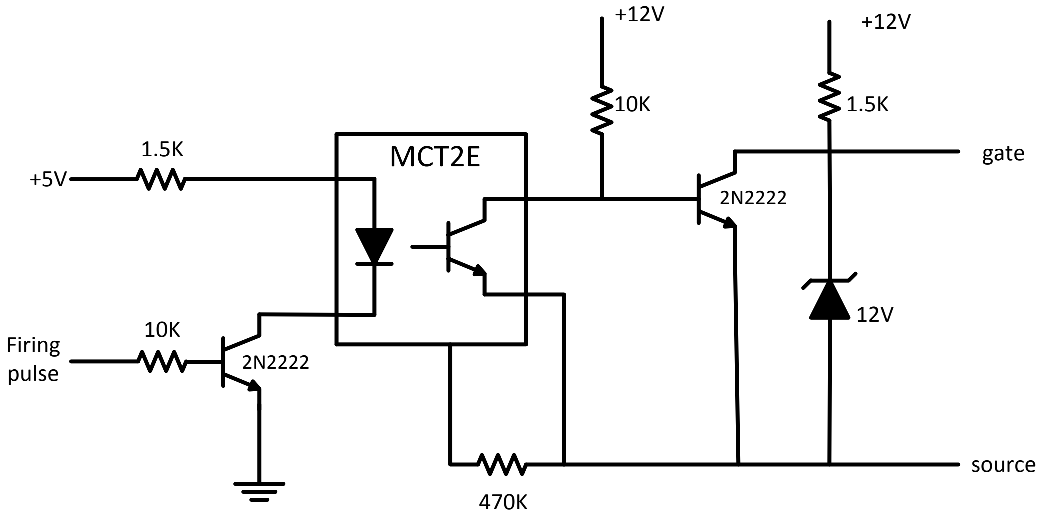

Figure 5.4 Schematic of pulse amplification and isolation circuit

5.1.4 Snubber Circuit

When switching mosfets at high frequencies, the current and voltage transients can exceed the rated value. To protect the MOSFET from high (di/dt) and (dv/dt), snubber circuits are used. Snubber circuit consists of a high power snubber resistance and capacitor In addition to this, a Metal Oxide Varister (MOV) is used to protect the switch from over voltage.

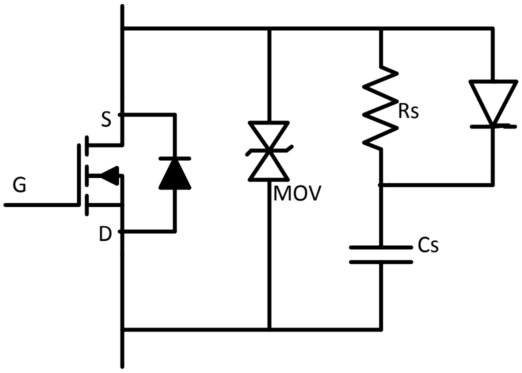

Figure 5.5 Schematic of snubber circuit

Figure 5.6 Image of the switch driver circuit

5.1.5 Current Sensing circuit

To obtain feedback in the circuit, current sensors have been used to estimate the State of Charge of the batteries. In addition to this, the current sensors have also been used to measure currents flowing through the switches and the inductor. The current sensor used is HTP25 with arrange to measure 25A current in either direction. This is basically a hall effect sensor that also provides galvanic isolation between its output (control circuit interface) and input (power circuit). If N_p turns of the input current carrying wire I are wound on the sensor, then the sensor transforms this current at the output as ($N_pI/1000$). Using a resistance Ro accross the output terminals, the current is converted to a suitable voltage. In order to interface this voltage with the microcontroller input pin, 3 levels of op amp gain circuits are connected to the output of the sensor.

- A buffer circuit is used to improve the drive of the output signal.
- A scalar is used to provide a suitable constant gain. The gain is adjusted by selecting the proper feedback resistance
- An adder circuit to add a fixed offset to the output. This is required when it is desired to measure bi-directional current bipolar output but the microcontroller ADC can only take unipolar input.

The current sensors were tuned using potentiometers. The adder is used to provide an offset of 2.5 volts. The scalar is used to set the gain so that greater magnitude among Imax and Imin corresponds to 5V or 0V respectively.

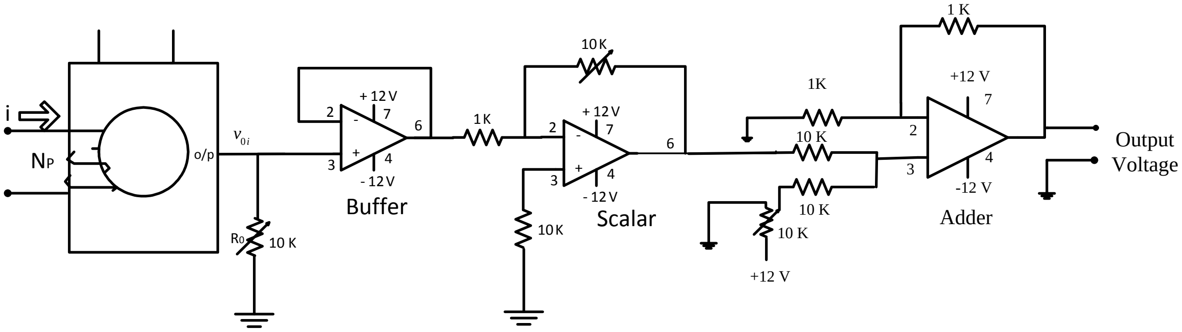

Figure 5.7 Schematic of the current sensor circuit

5.1.6 Power Supply

Dc Regulated supplies (+12V, gnd, -12V) are required for providing biasing to various circuits like pulse amplification and isolation circuits, current sensing circuits etc. using ICs 7812 for

+12V, IC 7912 for -12V. The circuit diagram of the regulated DC power supplies are shown in following figures:

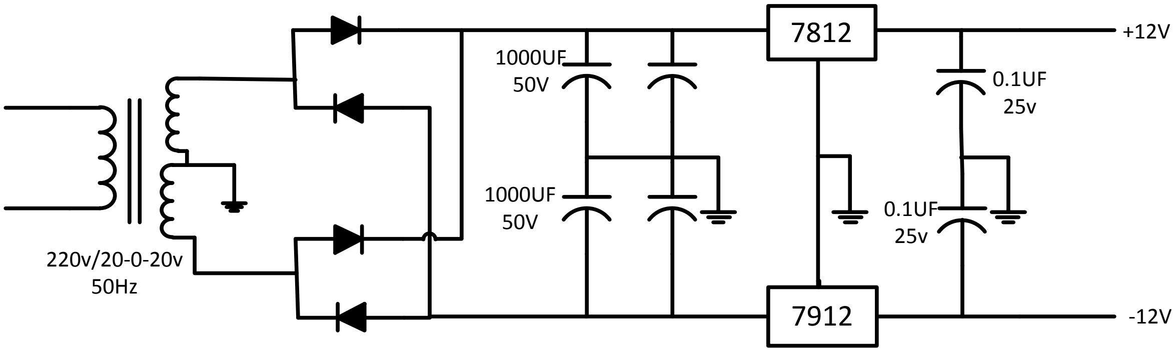

Figure 5.8 Schematic of +12/12V power supply

5.1.7 DC charging current

In order to get a desired charging current, a dc supply was made using an auto transformer and a bridge rectifier setup. This was then connected in series with a rheostat and the batteries to be charged. The charging current was maintained almost constant by adjusting the autotransformer and rheostat as and when needed.

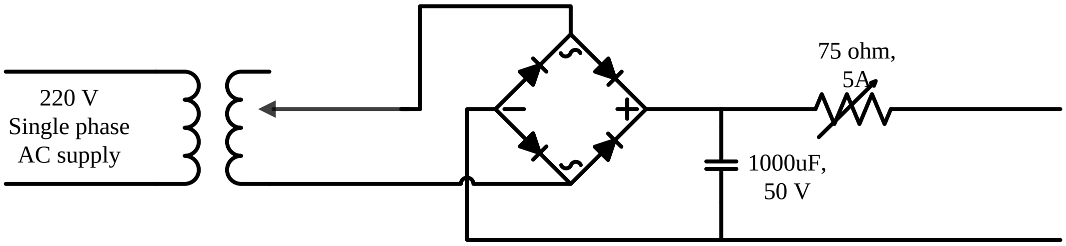

Figure 5.9 Schematic for the dc supply used for charging the batteries

5.1.8 Microcontroller

To generate gate signals for switches and to control the state machine of the circuit operation i.e. changing between equalizing and dead phase, a digital microcontroller was used. The Arduino

Mega 2560 is a microcontroller board based on the ATmega 2560. The on chip peripherals on the board include54 digital I/O pins, 16 analog inputs interfaced with the ADC on board. The relevant technical specifications are as follows:

- It is a 5V digital system.
- It consists of a 10 bit ADC and hence provides an input analog voltage resolution of 5/1024 = 0.049 V, which is sufficient to measure all dynamic changes in the balancer circuit.
- It has a 16MHz clock which is more than sufficient to generate switching gate pulses on the digital pins of about 10kHz

The programs written in the controller to perform various tasks are presented in the appendix.

5.2 Hardware Results

Using the hardware setup described in the previous section, the working of the prototype was verified at different levels. The details of the hardware testing process are presented here in detail. The circuit was tested for two series connected batteries (B1, B2) where B1 was deliberately kept at higher initial state of charge than B2. The simplified version of the circuit, consisting of two switches only, is redrawn here for reference.

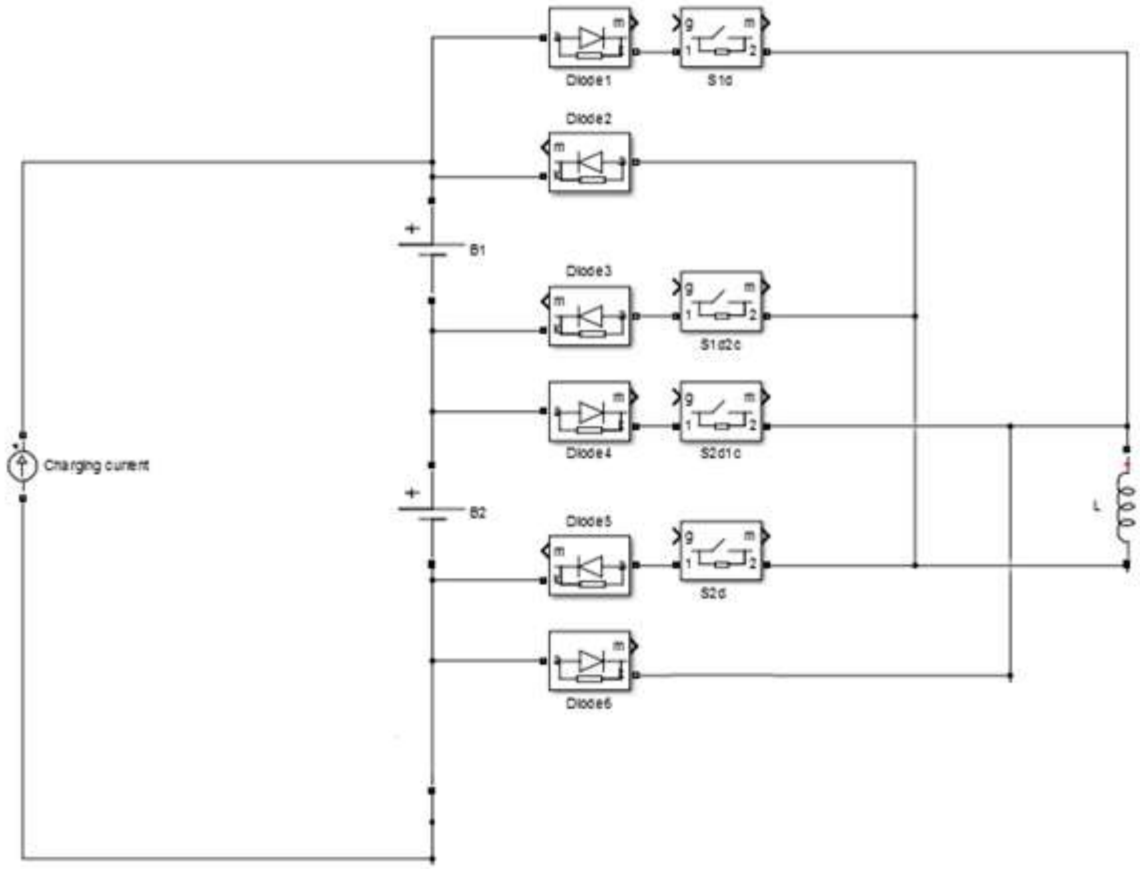

Figure 5.10 Schematic of the hardware circuit being tested

By discharging the batteries by unequal amounts, a deliberate change in SOC was created between the batteries. Using the curve of open circuit voltage (O.C.V) vs state of charge (SOC) for 12V lead acid batteries the batteries could be discharged to desired values of SOC.

Initial OCV of B1 = 12.55 V.

Initial SOC of B1 = 80%. (approx.)

Initial OCV of B2 = 12.39 V.

Initial SOC of B2 = 70%. (approx.)

The charging current kept constant at 0.5A.

Following the design guidelines, the values of circuit parameters were set as

The inductance value of the available inductance = 1mH.

The switching frequency was chosen to be = 2 kHz; Duty cycle, D = 0.4.

$t_{eq\,=}$ 20 min ; t_{dead} = 10 min.

On the basis of these values, the charge transfer occurring between batteries was calculated as follows.

During the equalizing phase,

Charge discharged by B1 to B2 (using equation 3.3)

$$\boldsymbol{Q_{dis}} = \frac{1}{2} \times \boldsymbol{DT_s} \times \boldsymbol{ipeak} \;\; = \frac{1}{2} \times \frac{V_{B1}}{L} \times (DT_s)^2$$

Charge discharged by B1 to B2 = 0.24 mC

This charge is lost in one 500 microsecond switching cycle. Thus, charge discharged in 20 min = 576 C which is a 2.22% reduction in state of charge for B1.

This charge is transferred to B2 and a 2.22% increment should be found in B2.

In addition to this, due to the charging current $I_{charging}$, both batteries will absorb charge of

($I_{charging}$ * 20 min * 60) = 600 C, which is a 2.31% increment in the state of charge.

During the dead phase,

Both the batteries absorb a charge of 300 C in 10 min, which is a 1.15% increment in state of charge.

Therefore in one equalizing phase,

Net change in SOC for B1 = + 0.1%

Net change in SOC for B2 = +4.5%

In one dead phase, net change in SOC of both B1 and B2 = +1.15%

To verify these calculations, the SOCs of B1 and B2 were observed with time. After assuming the initial SOCs from the open circuit voltage, these values were fed to the microcontroller. In the code, the SOCs were estimated by coulomb counting method. Battery currents were measured via the current sensors and these were integrated with time in the controller. The SOCs measured by the microcontroller were displayed on the screen every 5 minutes. In this way, SOCs of the batteries were measured with time. The microcontroller executes the state machine starting from the equalizing phase.

The observed values of SOC are tabulated here.

Time (Min)	Battery1 SOC (%)	Battery2 SOC (%)
5	80.00	71.11
10	80.00	72.24
15	80.02	73.2
20	80.03	74.34
25	80.38	74.84
30	80.95	75.29
35	81.06	76.33
40	81.07	77.42
45	81.14	78.61
50	81.17	79.89

The data was used to plot a graph of SOC vs time. The graph below shows the observation of SOC with time.

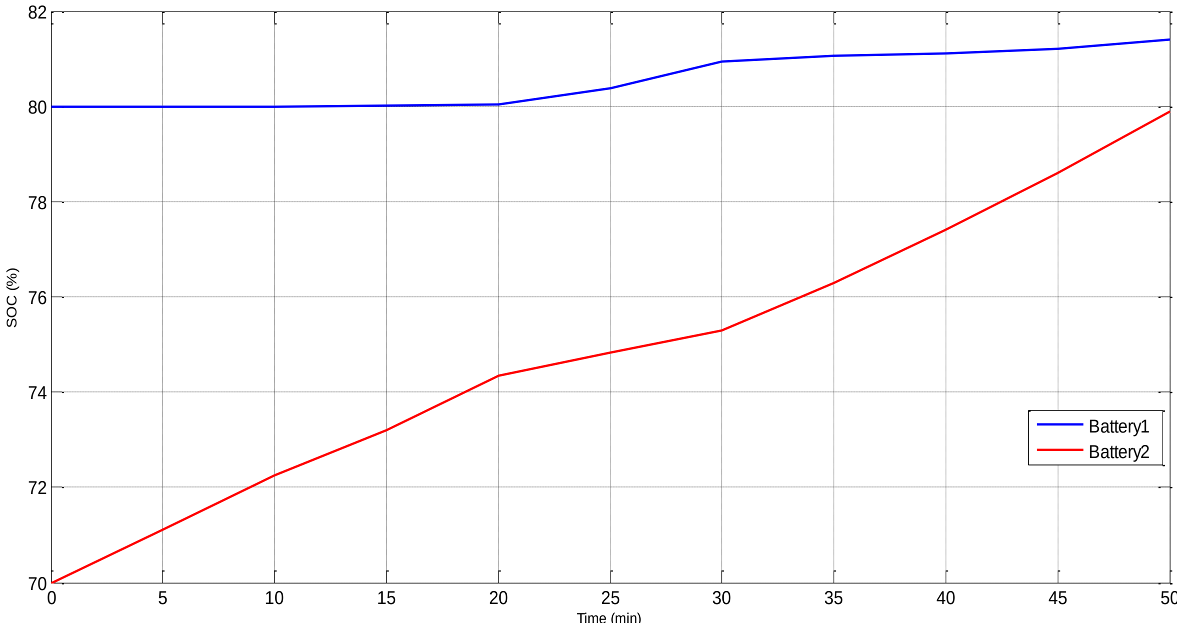

Figure 5.11 Battery SOC vs time during balancing

As seen from the graph, it is clear that the battery is able to circulate charge from B1to B2. The variation of slopes of the SOC lines shows that in these 50 min, the equalization phase ends at 20 min and resumes again at 30 min mark.

In addition to the cumulative charge transfer, current sensor outputs are used to measure currents at various points in the circuit. These instantaneous current waveforms were recorded in a digital storage oscilloscope (DSO) and the image of the waveforms was recorded.

During the equalization phase, the current waveforms through the switches S_{1d} and S_{1d2c} are shown in the image below. S1d carries current only until battery one discharges and is subsequently turned OFF. S_{1d2c} on the other hand also discharges this current from the inductor to battery B2. The theoretical nature of the waveform (buck boost type) can be found in figure 3.4. From the image below it can be inferred that waveforms of the same nature are observed and the qualitative behavior of the circuit is hence verified.

Figure 5.12 Image of the current waveforms in switches S1d (yellow) and S1d2c (blue).

Similarly, current carried by batteries is also recorded to verify the qualitative behavior of the circuit. The image of the same is presented here. It can be inferred from the image that the batteries conduct complementarily during the equalizing phase i.e. while one charges the inductor, the other discharges it.

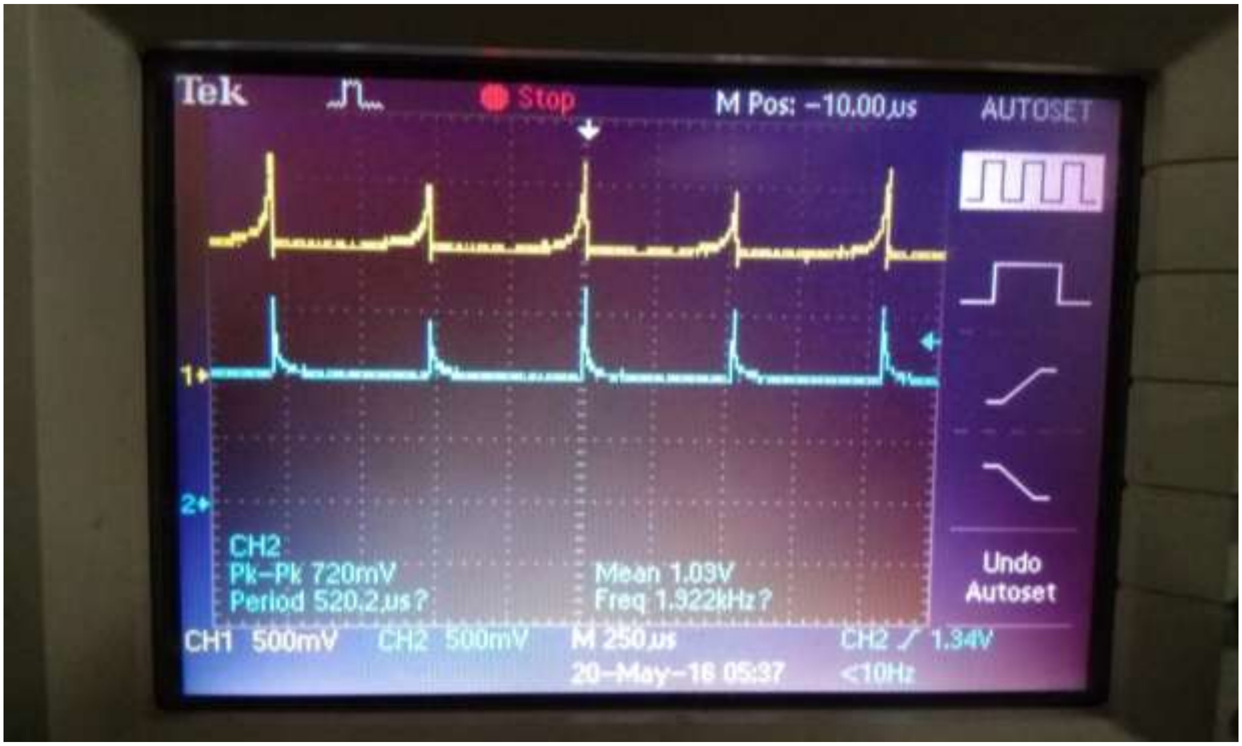

Figure 5.13 Current waveforms of B1(yellow) and B (Blue) during equalizing phase.

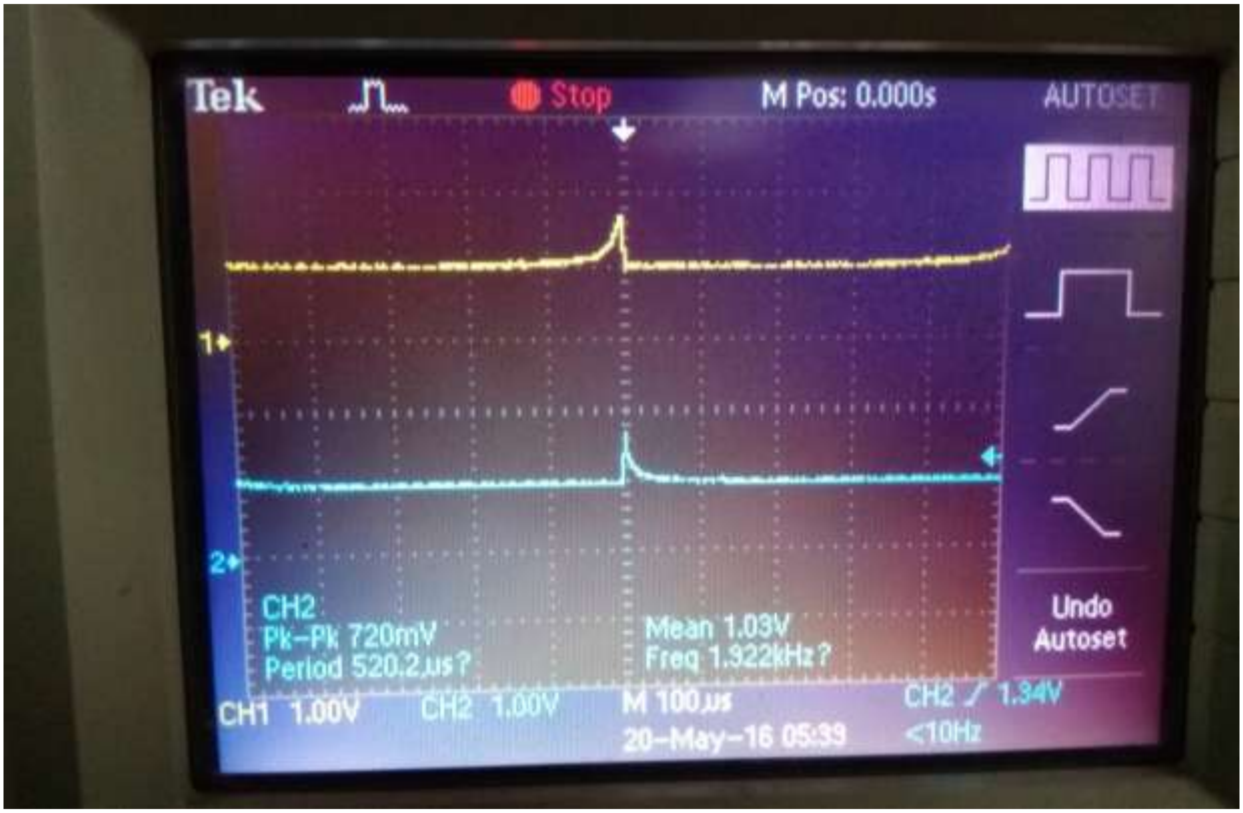

Figure 5.14 Complementary nature of Currents in B1(yellow) and B2 (blue)

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

In this chapter, we present the conclusive comments to the work carried out in this dissertation. After presenting a brief introduction to battery parameters and specifications, the problem of battery cell imbalance was explained in great detail along with its possible causes. The effects of battery cell imbalance on usable capacity of the whole pack are clearly stated. A considerable amount of discussion is dedicated to understanding the gravity of the battery cell imbalance problem. The need for battery balancing is thus justified to be of significant importance.

A large number of battery balancing circuits and methodologies can be found in literature. However the more common form of battery balancing found in the industry is passive balancing technology. Some of the most popular battery balancing circuits, both active and passive, were briefly reviewed. The superior advantages of energy efficiency in active balancing circuits are explained. One of the active balancing circuits namely the buck boost converter based charge balancing circuit or inductive charge shuttling circuit was studied in detail.

Buck boost converter based battery balancing circuit was studied in detail. An elaborate theoretical analysis was presented followed by MATLAB simulation of the circuit for various input test conditions. In the process of simulating the circuit, the behavior of the circuit was observed for variation in circuit parameters. Using the simple case of a 2 battery system, the simulation provides a proof of concept for the utility of the converter in transferring charge from higher charged batteries to lower charged batteries while charging is ongoing.

Lastly, a hardware prototype was built with MOSFETs as switches, current sensing and SOC estimating circuits and implemented using a microcontroller. The results were verified for a particular initial difference in battery SOCs for a two battery system. For conditions that are not too extreme, the prototype can verify the qualitative nature of the circuit quantities.

The potential advantages of this particular battery balancing circuit are that it

- implements the active balancing methodology and prevents energy losses unlike passive circuits

- has a relatively low equalizing time
- costs less since it contains few components and
- has a simple control scheme.

This circuit can be a cost effective solution to many battery management systems. While the problem of balancing becomes more complex when higher number of batteries are involved, most battery packs have a simple distinction of identifiable weak cells and strong cells. In such cases where repetitive behavior of cells is observed, the circuit can be implemented with ease.

6.2 Future Scope

The battery balancer presented here works in theory but several issues need to be considered for it to be usable as a commercially viable product:

1. The circuit must be able to work reliably for packs with higher number of batteries. With higher number of batteries and SOC disparities among them, the controller needs to solve a time scheduling problem to allot time appropriately for charging and discharging various batteries for different times for routing charge to and from the right place.

2. The hardware design of the circuit needs to be modularized so that batteries can be added or removed in series. The hardware must also have a compact form factor, to be able to fit into existing BMSs like a black box.

3. Methods of using charging within a given time limit should be introduced to keep the total charging time at a minimum.

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