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Passive and Active Battery Balancing Methods Implemented on Second Use Lithium-ion Batteries

Walter Bartek
Grand Valley State University

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Walter Bartek

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To my lovely wife who patiently encouraged me through this journey.

Acknowledgments

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Abstract

As the number of electric vehicles (EVs) increases, the number of used battery packs that require disposal increases; however, many of these packs still have useful capacity and can be repurposed. When using repurposed large lithium-ion battery packs, deviations between cells within a pack become problematic. These deviations result in a pack that is unbalanced, affecting performance and proving potentially hazardous when charging. Consequently, a battery management system (BMS) is needed. To provide safety, the BMS in this paper monitors and controls the operation of the battery pack. In addition, it controls the redistribution of charge between the cells within the pack, providing battery balancing and performance benefits. Two designs are prototyped and tested using repurposed battery packs.

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Chapter 1

Introduction

1.1 Problem Description

The number of batteries in use is ever increasing. Cell phones, laptop computers, electric vehicles (EVs), load balancing, and even powered yard tools such as electric lawn mowers all require power provided by battery packs. A low power device such as a cell phone may require no more than one cell to provide the require amount of power needed, but to meet the demands of high power applications such as EVs and load balancing, a large number of battery cells is needed. EVs, such as a Tesla model S, may use more than 8000 cells to supply the required power.

When new, the characteristics of the cells are similar and the pack will behave uniformly. These characteristics include capacity, open circuit voltage, self discharge, and internal resistance. Due to cell degradation over time, the number of charge discharge cycles lead to a decrease in uniformity between the cells in the battery pack. As cell degradation increases, the effects compound and cell degradation tends to accelerate. Overall, cell degradation leads to poor battery pack performance and potential safety issues.

In many battery applications, lithium-ion is the battery chemistry used. When compared to other battery chemistry, lithium-ion is more volatile and becomes unsafe when operating outside a small safe operating zone. Because of this, it is imperative that a battery management system (BMS) be used to help keep the batteries operating within a safe zone. Increased cell degradation makes it easier for some cells within a pack to operate outside of a safe zone. This can lead to catastrophic failure when charging. [1]

In addition to the safety issues present when using lithium-ion batteries, there is at least one more reason to make use of a BMS. As the number of charge cycles increases, each cell's state of charge will become unbalanced from the others. This affects the usable capacity of the battery as a whole in a negative way. Through the use of a BMS that can balance cells, the cell's state of charge can be brought closer together. This balancing can improve the battery's capacity

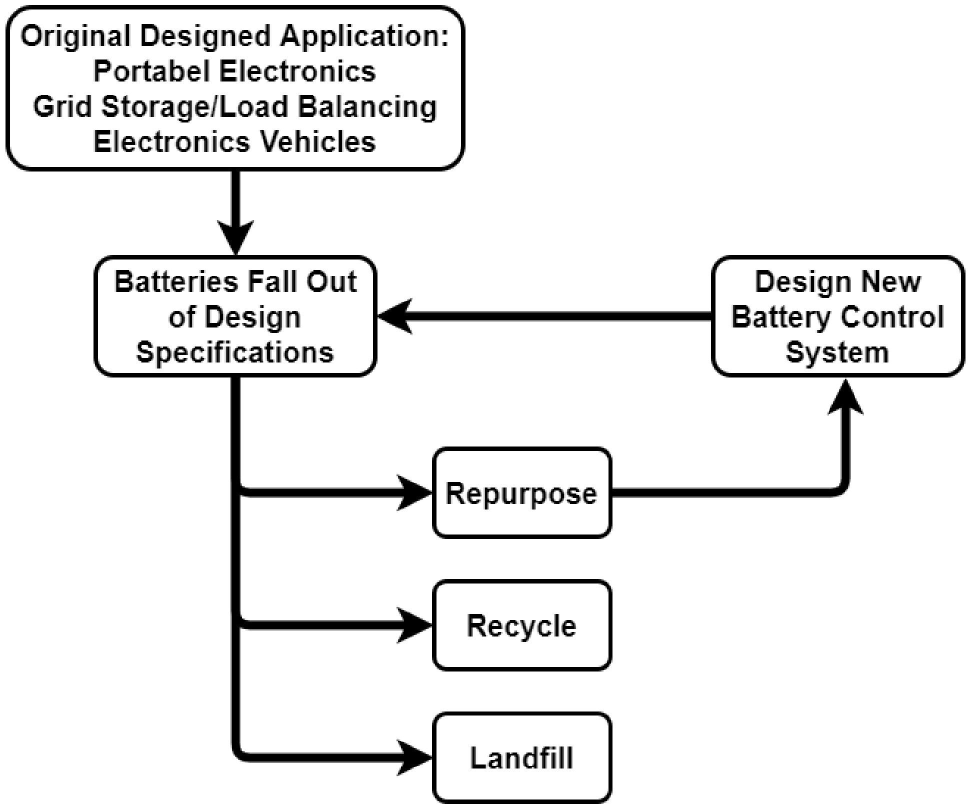


Figure 1.1: Battery Life Cycle

as all cells are now able to make use of more of their individual capacities. [1]

Though all cells experience some decrease in characteristics as they experience charge cycling, some cells in a pack may experience a significantly greater decrease than the rest of the cells. To maintain a pack in the presence of these weak cells and cell groups, the significantly worse cells should be removed and replaced. Often, however, the process to replace a cell or cell group that is affecting the pack is time consuming and costly. Instead of replacing a cell, or even a cell group, it can be preferable to simply mitigate the effect of the weak cells. Battery balancing can be helpful for this purpose.

Fig. 1.1 illustrates possibilities for a battery's life cycle. After a battery pack no longer conforms to the original design specifications, it is no longer usable as-is in its current application. Several things can be done with an out-of-specification battery: it can be tossed in a landfill, it can be recycled, or it can be repurposed. In EVs, a battery pack may be considered unusable when it is only able to supply 70-80% of its designed capacity; however, the pack is still usable for a different application such as energy storage for load leveling. If it is repurposed, a new battery control system needs to be designed for the repurposed battery pack to be used in a new application. After a time, the battery pack will again fall out of specification. Once again, the battery pack can be tossed, recycled, or repurposed. At some point, it will no longer make sense to repurpose a battery pack; at which point, it should be recycled. This thesis will focus on designing, prototyping, and testing two balancing BMS for use on a repurposed battery pack originally used in an EV.

1.2 Scope

This thesis explores the use of voltage monitoring, current monitoring, and charge balancing to extend the capacity of repurposed second life battery pack. This thesis specifically looks at balancing effects when applied to a used lithium-ion battery that has at least one weak cell group. Two different styles of battery balancing are considered: dissipative shunting and non-dissipative bi-directional fly-back transformer. Both styles are prototyped, but after initial testing, the non-dissipative bi-directional fly-back transformer balancer was chosen to be the focus and tested further. The non-dissipative balancer is able to be connected to a pack in multiple ways, and two specific connections were tested on a repurposed battery pack.

1.3 Layout of Thesis

This thesis begins with some background information about batteries and battery management systems in Chapter 2. This chapter defines battery terms and discusses what makes a battery, pros and cons of Lithium based batteries, and the performance of Lithium cells. It will also include information about the functions and types of BMSs and different balancer topologies. Chapter 3 contains the current draft of a paper that is in preparation for publication for this thesis. Chapter 4 presents further information about the balancers that were designed and built for this thesis. It also presents additional results not fully shown in the paper in Chapter 3. This is followed by Chapter 5 which discusses the results seen in the previous chapter and future work that could be done to further the work of this thesis.

Chapter 2

Background

To better understand the work this paper details, background information is needed. To this end, information regarding batteries and battery management systems is provided in this chapter. Batteries will be covered in Section 2.1. This section will include an overview of the components that make up a cell, a classification of different types of batteries, the operation of a cell, factors that affect a battery's performance, and specific information about lithium-ion batteries. Following this, information about BMSs will be provided in Section 2.2. This section includes information about BMS functions and different types of BMSs.

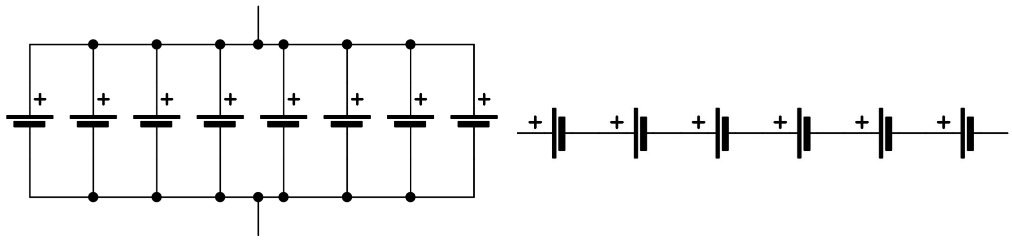
2.1 Batteries

2.1.1 Definitions

When talking about battery packs, there is often some confusion about what is actually being said. It is not uncommon for someone to just say ”battery” when they are actually referring to a cell, a block, or a pack. To mitigate confusion moving forward, the terminology used in this paper for referring to different components of a battery pack are as follows [1]:

- *Cell*: a single, basic battery element. An example of this is a single Li-Ion 18650 providing 3VDC to 4VDC;
- *Block*: a group of cells wired in parallel to provide the same voltage as a single cell;
- *Battery*: a group of cells or blocks connected in series to provide a voltage greater than that of a single cell;
- *Pack*: a group of batteries in a parallel and/or series combination.

Cells are connected in different combinations of parallel and series to create larger groups. Fig. 2.1a shows a block of 8 cells in parallel. Fig. 2.1b shows a battery of 6 cells in series. Combining series and parallel combinations of cells



(a) (b)

Figure 2.1: (a) Series Cells (b) Cell Block (parallel cells)

allows for a battery pack to be made. Fig. 2.2 depicts two examples of a battery pack of 48 cells. Fig. 2.2a shows a battery pack of 6 series connected blocks of 8 parallel cells; the shorthand for this configuration is 6s8p. Fig. 2.2b shows the same 48 cells but connected in 8 parallel strings of 6 cells in series; this configuration is written as 8p6s. Connecting blocks in series is generally a safer approach than connecting series strings in parallel. It is more likely that a single cell in a series string operates outside the safe operating zone during charge or discharge than for a block of parallel cells to leave the safe zone. [1]

2.1.2 Specifications of a Cell

For all battery chemistries, there are specifications used to describe the characteristics of those cells. The nominal voltage of a cell is the direct result of the chemistry used. Nickel-based chemistry often produces a nominal voltage of 1.2 VDC while a lithium-based chemistry will produce a nominal voltage over 3.0 VDC. The nominal capacity of a cell indicates how much charge a cell is able to store. This is often given in ampere hours (Ah) or milliampere hours (mAh). The C rate of a cell is directly related to the capacity. It is a measure of the current a given cell is able to consistently sink or source for an hour. For a 10 Ah cell, 1C would be 10 A as the cell would be able to charge or discharge at a rate of 10 A for an hour. The energy stored in a cell is its nominal voltage multiplied by its nominal capacity, yielding an energy in Watt-hours. The instantaneous power of a cell is its energy release rate. [2]

While voltage and current are able to be directly measured, two specifications of a cell that are not able to be directly measured are State of Charge (SoC) and State of Health (SoH). The SoC of a cell is a ratio of the available capacity in the cell versus the total capacity the cell is able to hold when fully charged. SoC depends on a Li concentrations on an electrode. Unlike voltage which depends on the surface concentration, SoC is dependent on average concentrations. SoH is a measure of the cells aging. A decrease in capacity and an increase in internal resistance can indicate the age of a cell. Both SoC and SoH require battery models to be estimated. [3], [4]

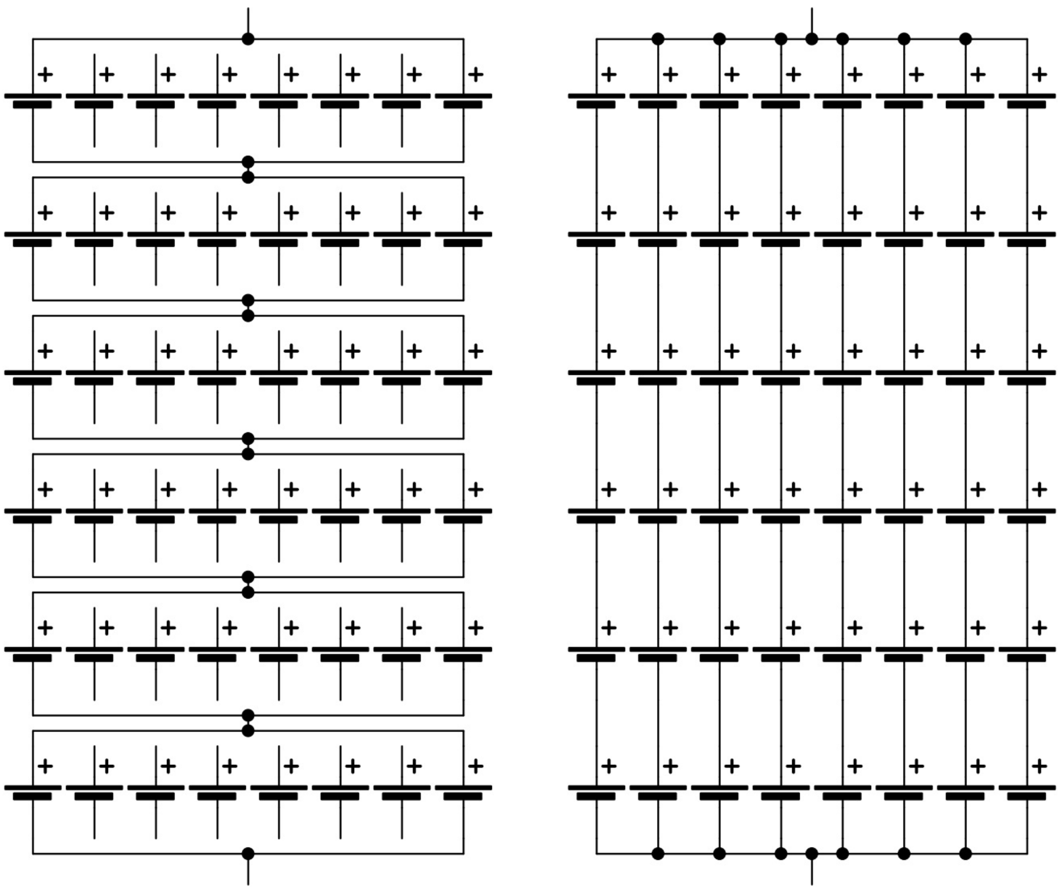


Figure 2.2: (a) Battery Pack of Series Connected Blocks (6s8p). (b) Battery Pack of Parallel Connected Series Strings (8p6s).

2.1.3 Components of a Cell

To produce electrical energy, a cell undergoes an electrochemical reaction. This reaction is typically an oxidation-reduction reaction that converts the chemical energy to electrical energy. For a rechargeable cell, this reaction is reversed through the application of electricity allowing the cell to undergo this electrochemical reaction many times. The reaction happens by means of a transfer of electrons between different materials creating a circuit. There are three main components that make up a cell and allow this electron transfer to occur. These components are as follows [5]:

- *Anode*: the negative electrode. The anode is the reducing electrode. It provides the electrons to the external circuit and is the electrode that experiences oxidation during the oxidation-reduction reaction.

- *Cathode*: the positive electrode. The cathode is the oxidizing electrode. It accepts the electrons from the external circuit and is the electrode that experiences reduction during the oxidation-reduction reaction.

- *Electrolyte*: the ionic conductor. The electrolyte is the solution through which ions can travel between the anode and cathode. It is typically a liquid solution, though some cells use solid or gel-type electrolytic conductors instead.

The designations of anode and cathode being the negative electrode and positive electrode, respectively, are for discharge. When a cell is being charged, the negative electrode becomes the cathode and the positive electrode becomes the anode, however they are generally referred to by their respective functions during discharge. [6]

There are two main classifications for an electrochemical battery: primary and secondary. A primary cell or battery is also known as non-rechargeable while a secondary cell or battery is also known as rechargeable. The difference between the two classifications being whether or not the cell or battery can be electrically recharged with ease. Primary batteries are one time use while secondary batteries can be recharged for multiple uses.

A secondary cell operates during discharge and charge. The discharge of a cell happens when an external load is connected to the cathode and anode completing the circuit. With the load connected, electrons are able to flow from the anode, through the load, to the cathode. This is made possible by the oxidation-reduction happening inside the cell. The anode is oxidized, and the cathode is reduced. Anions and cations flow through the electrolyte to the anode and cathode, respectively. The charging of a cell happens when an electric current is applied in the opposite direction as that experienced during discharge. This causes reduction of the negative electron and oxidation of the positive electron. By definition, the anode is the electrode that experiences oxidation, and the cathode is the electron that experiences reduction. This means that during charging the cathode is the cell's negative electrode, and the anode is the cell's positive electrode. [5]

While it has the same main components as an electrochemical batttery, a lithium based battery does not work in the same way an electrochemical battery does. While electrochemical batteries use a redox reaction, lithium batteries use

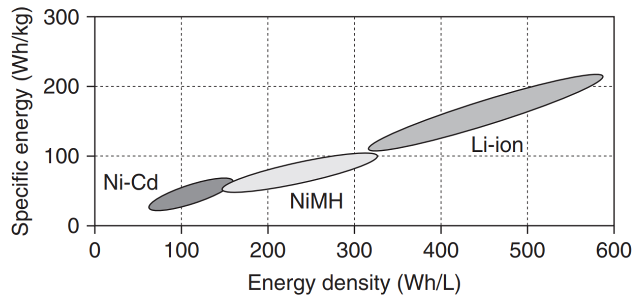


Figure 2.3: Energy Density of Rechargeable Cells [5]

intercalation. This means that lithium is stored in the electrodes with Li^+ moving through the electrolyte. Li^+ becomes Li by entering an electrode when an electron is available and Li becomes Li^+ by exiting an electrode and giving up an electron. [7]

Advantages of lithium based cells:

- higher energy density (see Fig. 2.3)
- generally need fewer cells in series than with other chemistry as they have a higher nominal voltage
- low cell discharge rate

Disadvantages of lithium based cells:

- more expensive than other electrochemical batteries
- more complex manufacturing process
- strict voltage operating range
- strict temperature operating range
- more volatile than electrochemical batteries and require more care to keep them operating in a safe zone

2.1.4 Lithium-ion Chemistry

Lithium-ion batteries, as other types of batteries, function through a chemical reaction. Lithium-ions travel between the batteries anode and cathode during this reaction: from the anode to cathode during discharge and from the cathode to the anode during charging. When referring to Lithium-ion batteries, one may be referring to one of many different chemical compositions that are often just referred to as Lithium-ion. A few of these chemistry are as follows:

$LiCoO_2$: Lithium-cobalt-oxide

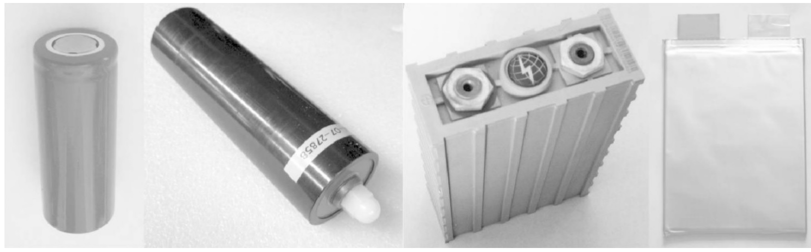


Figure 2.4: Different formats of Lithium-ion Batteries [1]

$LiFePO_2$ and Li_2FePO_4F: Nano-phosphate/lithium-iron-phosphate/lithium-ferro-phosphate

$LiNiO_2$: Lithium-nickel-oxide

With changes in chemistry come changes in nominal voltage, energy, and power density. The chemistry of the batteries focused on for the research in this paper is $LiFePO_2$; this chemistry has a nominal voltage of 3.6V. [1]

2.1.5 Lithium-ion Cell Formats

Just as Lithium-ion batteries are available with different chemistry, Lithium-ion batteries are also available in different formats. Several of these formats are seen in Fig. 2.4.

The formats seen in Fig. 2.4 are small cylindrical, large cylindrical, prismatic, and pouch, respectively from left to right. What is seen in Fig. 2.4 are individual battery cells. Each of these battery cell formats has advantages and disadvantages. The small cylindrical format is popular for its physical strength and ease of production. This is the type of battery used in this thesis. [1]

2.1.6 Effects of Aging on Lithium-ion Batteries

As a lithium-ion cell ages, physical changes occur inside the cell that lead to changes in its characteristics, which are negatively affected leading to a loss of capacity. This loss of capacity in each individual cell has a negative effect on the battery pack as a whole and lowers the pack capacity. As each cell is not exactly the same due to manufacturing tolerances, the changes in characteristics experienced by one cell are not the same as another. This can lead to one or more cells losing significantly more capacity than the rest of the cells over time.

As previously mentioned, lithium-ion cells have a volatile chemistry. Because of this, care needs to be taken when charging and discharging lithium-ion cells, especially after aging has occurred. When charging, it is easy to damage the battery due to over voltage. When this happens, not only is the cell damaged, there is risk of overheating causing the electrolyte to ignite. During discharge, there is a risk of irreparable damage due to an over-discharge. As cells age, the divergence of characteristics between cells results in increasingly dissimilar cell voltages during charge and discharge, increasing the risk of an over voltage or under voltage condition.

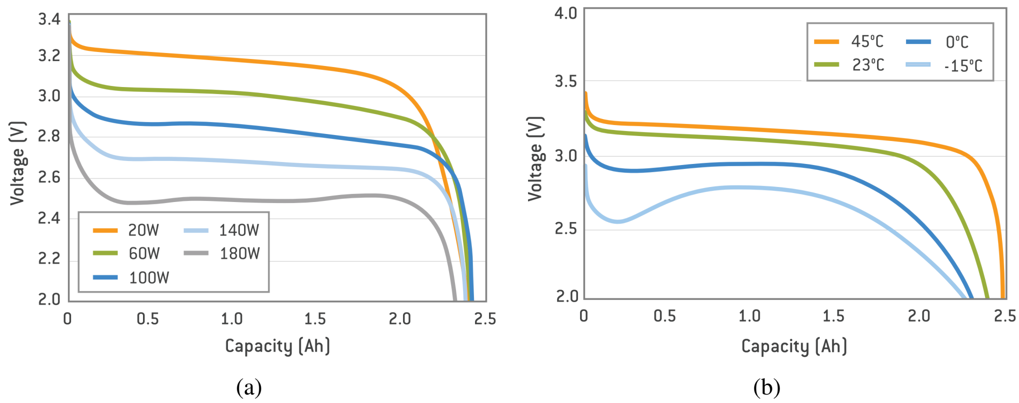


Figure 2.5: (a) Constant Power Discharge at 23°C [8] (b) Constant Current Discharge at Various Temperatures [8]

2.1.7 Cell Performance

There are quite a few things that can affect the performance of a cell over its life cycle. Some of these factors do not affect the long term performance of the cell but more the way in which performance is perceived. The voltage level of a cell has several facets to it. First, there is a theoretical voltage based on the chemistry of the battery. This is the highest voltage of the cell. Next, the open-circuit voltage is the voltage measured when the cell is not under load. This will be lower than the theoretical voltage due to physical imperfections. The closed-circuit voltage is the voltage measured while the cell is under load. This voltage will be even lower than the open-circuit voltage due to voltage dropping across the internal resistance. As the current draw increases, the voltage drop will increase.

The way in which a cell is discharged has an effect on its immediately usable capacity as well as its total life. A smaller current draw during discharge means a smaller voltage drop due to internal resistance. This means that more of the cell's capacity is able to be used before reaching its lower cutoff voltage. The voltage drop over the internal resistance effectively raises the lower cutoff voltage. This means that less of the cell's capacity is able to be used. Also, higher discharge currents create more stress on the cell and negatively affect the chemistry of the cell leading to a shortened life. If a cell has the current drawn in bursts rather than continuously, it will recover a small amount of capacity between bursts. Fig. 2.5a shows how different constant power draws, which correlates to different current draws, affect the cells performance: a higher draw has a higher affect.

The operating temperature of a cell has a significant impact on its life. Lower temperatures lead to an increase in internal resistance and reduced chemical activity. Fig. 2.5b shows this relationship. This means that at lower temperatures, the cell will have a lower voltage and lower effective capacity. As the temperature of the cell increases the internal resistance will decrease and the chemical activity will increase as well. This will lead to a higher voltage and a higher capacity. That is until the cell becomes too hot. When the cell temperature increases too much, the cell chemistry can become volatile and begin to react without an external load. This can lead to thermal runaway where removing load from the cell does not reduce the cell's self induced temperature. During thermal runaway, a cell will

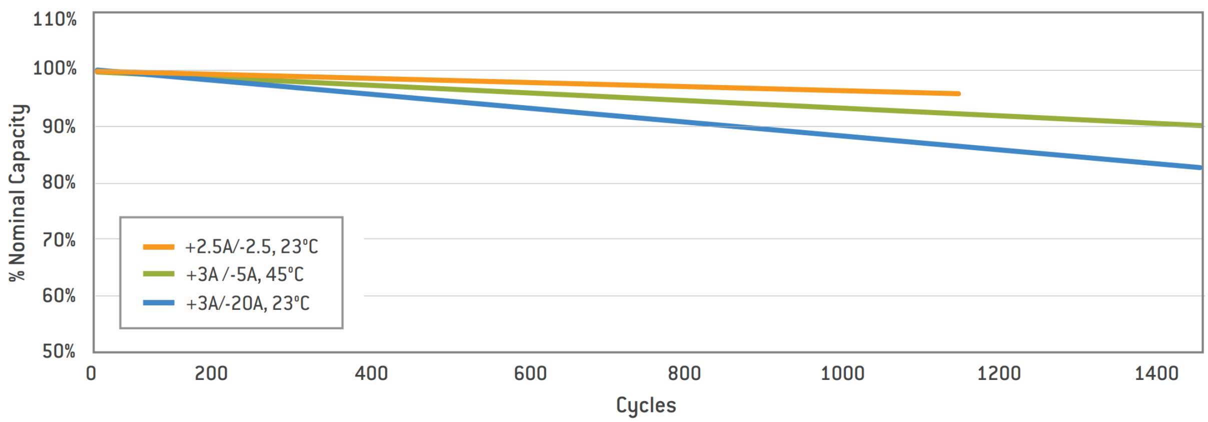


Figure 2.6: Cycle Life Performance, Full Discharge, Various Temperatures and Discharge Rates [8]

vent gases, produce flames, and in some cases, explode.

Voltage, current draw, and temperature all affect a cell over its lifetime. With each discharge-charge cycle, a cell's performance degrades. This impacts capacity, internal resistance, and how likely a cell is to deviate from other cells and leave the safe operative zone. Fig. 2.6 shows how cycle life performance under different conditions can affect a cell. [5]

2.2 Battery Management Systems

The most basic function of a battery management system (BMS) is to monitor a battery or pack and allow the user to see if the battery is operating within its designed parameters. For a lithium battery, this is very important as operating outside the safe zone is dangerous. While a BMS should, at a minimum, be used for monitoring the battery, a BMS can also be designed to make more effective use of the energy stored in the battery. While it is desirable to have additional functionality, the cost and complexity often means limited functionality is implemented.

2.2.1 Functions of a BMS

There are a variety of functions that can be designed into a BMS. Those features will vary in importance depending upon the specific application. The simplest of BMSs may only measure the voltage of the cells within the battery pack. While simple, it offers the minimum amount of information needed for a user to keep a battery pack operating within the safe operating zone. A step up from this basic monitoring is load control. When a BMS is able to control the connection to between the battery pack and the load, it is able to disconnect a load or charger and protect the cells within the battery pack without intervention from the user. A BMS that includes a way of balancing the charge distribution of the cells within a battery pack is further able to maximize the performance of the battery pack. To maintain safety and cell health, though, a BMS needs to, at minimum, perform the following functions: [1]

Table 2.1: BMS Feature Comparison

				Protect During	
	Measure	Report	Balance	Charging	Discharging
Meters	X	X			
Monitors	X	X		X	X
Balancers	X	X	X	X	X

- Limit cells from being charged beyond their safe upper voltage limit by removing the charge current or informing the user that the charge current needs to be removed.
- Limit cells from being drained beyond their safe lower voltage limit by removing the load or informing the user that the load needs to be removed.
- Limit the temperature the cells are subjected to through limiting charge current, limiting discharge current, applying cooling, or requesting any of these options.
- Limit the charging current from exceeding a safe value by controlling the charge current or requesting a reduction of the current.
- Limit the discharge current from exceeding a safe value by controlling the discharge current or requesting a reduction of the current.

2.2.2 Types of BMS

BMSs are generally categorized by the functions that they perform. Several types of BMS will be discussed: meter, monitor, and balancer. These BMSs range from relatively simplistic to complex.

A meter simply measures different parameters of a battery pack. This generally includes measuring the voltage of the cells within a pack, but other parameters may also be measured. Current and temperature are two other common parameters to measure. Some meters make use of algorithms to make estimates of hidden parameters such as State of Charge (SOC) and State of Health (SOH). The measured data is often recorded and reported on a display for the user.

A monitor often provides the same functionality as that of a meter but adds the addition of autonomy. While a meter does not include any way to control the battery pack, a monitor is able to communicate with other connected devices such as the load and charger. This allows the monitor to request a reduction in current or completely stop the current. A monitor is not able to make any changes to the internal pack current as it operates by controlling devices that interact with the battery pack as a whole.

A balancer is more complex than a monitor. Unlike a monitor, a balancer is able to maximize the performance of the battery pack. Usually, the design of a balancer is not as a standalone device but as part of the BMS as a whole. As a standalone device, a balancer should have communication functionality to relay data to other parts of the BMS. The balancer will be the main focus of this thesis. [1]

2.3 Balancer Topologies

In this thesis, two types of balancer topologies are explored: dissipative and non-dissipative. Dissipative topologies use a resistive load to burn off excess charge through thermal energy. Active topologies, on the other hand, attempt to make use of all of the charge in a battery by shuttling charge between cells or between a cell and the battery as a whole. [9], [10]

2.3.1 Dissipative

Balancing circuits with a dissipative topology are often also referred to as passive or shunting balancers [9], [10]. Dissipative balancing circuits are often more simple and inexpensive when compared to non-dissiptive balancing circuits [11], [12]. The way in which a dissipative balancer generally works is straightforward. The excess charge is, as the name implies, dissipated. Generally, the shunt element is placed across one cell and dissipates the excess charge of that cell as heat while the charging of the other cells is uninterrupted. A shunt element is needed for each cell in the series string. All of the shunts are able to be turned on at the same time. For the shunting element to protect the cell from overcharge, the shunting element needs to be able to pass as much current as the charger supplies.

One of the simplest shunting elements used in a dissipative balancer is a switched resistor. An example circuit is seen in Fig. 2.7 [9]. Once the switch is engaged, the resistor shunts some or all of the current around the cell. This is done once the voltage of the cell reaches its maximum charging voltage. Another dissipative balancer design is the analog shunting balancer. An example circuit is seen in Fig. 2.8 [9]. Unlike the switched resistor design, the analog shunting balancer is able to adjust the amount of current shunted. This means that as the cell's voltage increases the charge being shunted can increase and slow down the current going to the cell until it is fully charged.

Dissipative balancers allow for a simple system that is able to protect cells in a series stack from being overcharged. They can be inexpensive when compared to more complicated balancing methods. They do, however, waste energy by turning the excess into heat. This dissipated heat can cause issues. Along with wasting energy, dissipative balancers are not able provide balancing while the battery is discharging. This makes them a viable solution for someone who does not need to worry about wasting energy but is more concerned with initial cost. An analog shunting balancer was designed, built, and prototyped for this thesis.

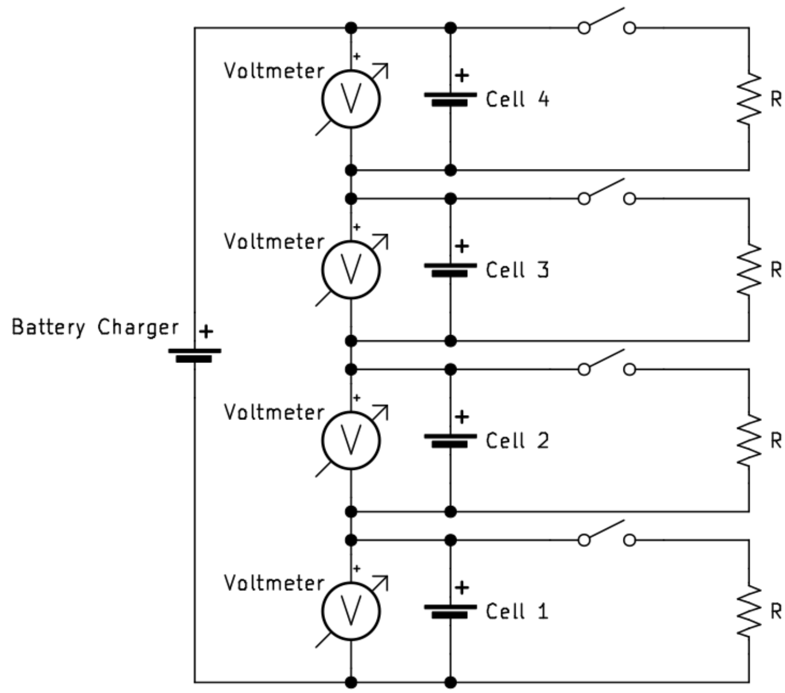


Figure 2.7: Switched Resistor Balancer

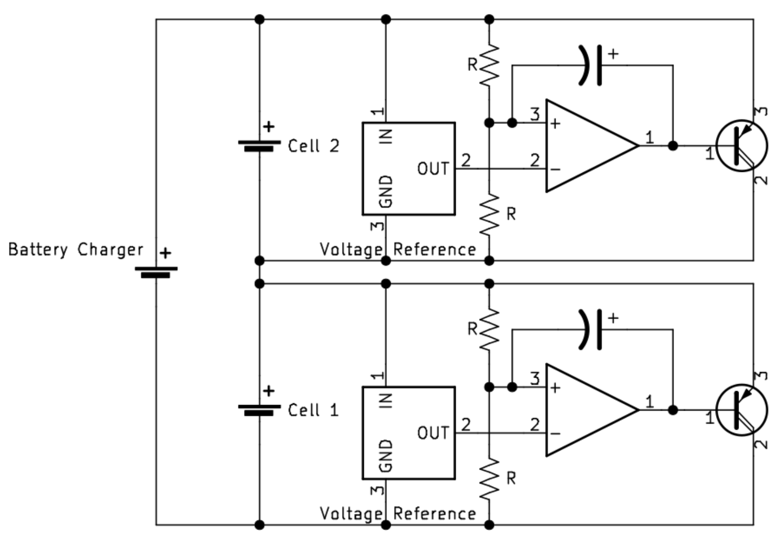


Figure 2.8: Analog Dissipative Balancer

2.3.2 Non-Dissipative

While there are some non-dissipative balancing topologies that are passive, most non-dissipative balancing topologies are considered active or dynamic balancers. This is because they require a more sophisticated switching circuit that needs some form of control circuit, often in the form of an micro control unit (MCU). There are three ways in which a non-dissipative balancer transfers energy: cell-to-cell, cell-to-pack, and pack-to-cell [12]. The last two may also be combined in a balancer. This is often referred to as a bidirectional balancer.

Cell-to-cell balancing requires an energy storage device, typically a capacitor (most common) or an inductor is used. Two methods of using a capacitor to transfer charge between cells are the switched capacitor and single switched capacitor. An example of a switched capacitor circuit is seen in Fig. 2.9 [10]. As is seen in the circuit, there are $n-1$ capacitors for a series pack of n cells. In this configuration, the capacitor stores energy from one cell and is able to transfer it to the adjacent cell. The next switching capacitor configuration is the single switched capacitor balancer, as seen in Fig. 2.10 [10]. In comparison to the switched capacitor balancer, the single switched capacitor blanacer only uses one capacitor. This capacitor is then connected to any cell in the pack through switches. While the switched capacitor balancer is only able to transfer charge between adjacent cells, the single switched capacitor balancer is able to move charge from one cell to any of the other cells in the pack. A disadvantage of the single switched capacitor balancer is that it is not able to transfer charge to and from multiple cells simultaneously while the switched capacitor balancer is.

Cell-to-cell balancing is generally based on energy storage through a capacitor or resistor. Cell-to-pack and pack-to-cell balancing is instead based around energy conversion. One method of cell to pack balancing uses boost converters connected to each cell and the battery pack as a whole. When turned on, the boost converter transfers charge from one cell to the pack. To perform pack to cell balancing, buck converters can be connected between the battery pack and each cell. When turned on, the buck converter transfers charge from the battery pack to the cell. Combining these two approaches allows for cell-to-pack and pack-to-cell balancing.

Another method to perform cell-to-pack and pack-to-cell is through the use of transformers. A multiple winding transformer can be used for this, but problems can arise if there are differences in the multiple windings inside the transformer; instead, multiple transformers can be used. A balancer made using multiple transformers in a flyback circuit was made and tested for this thesis. An example of this layout is seen in Fig. 2.11 [10].

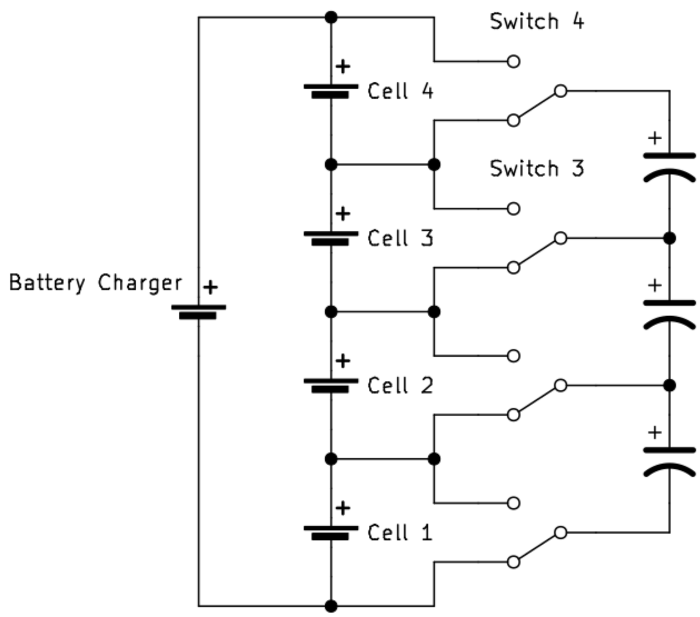


Figure 2.9: Switched Capacitor Balancer

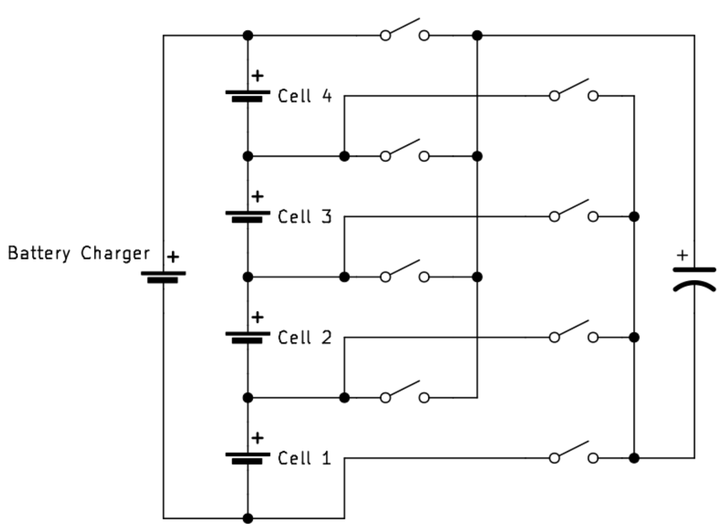


Figure 2.10: Single Switched Capacitor Balancer

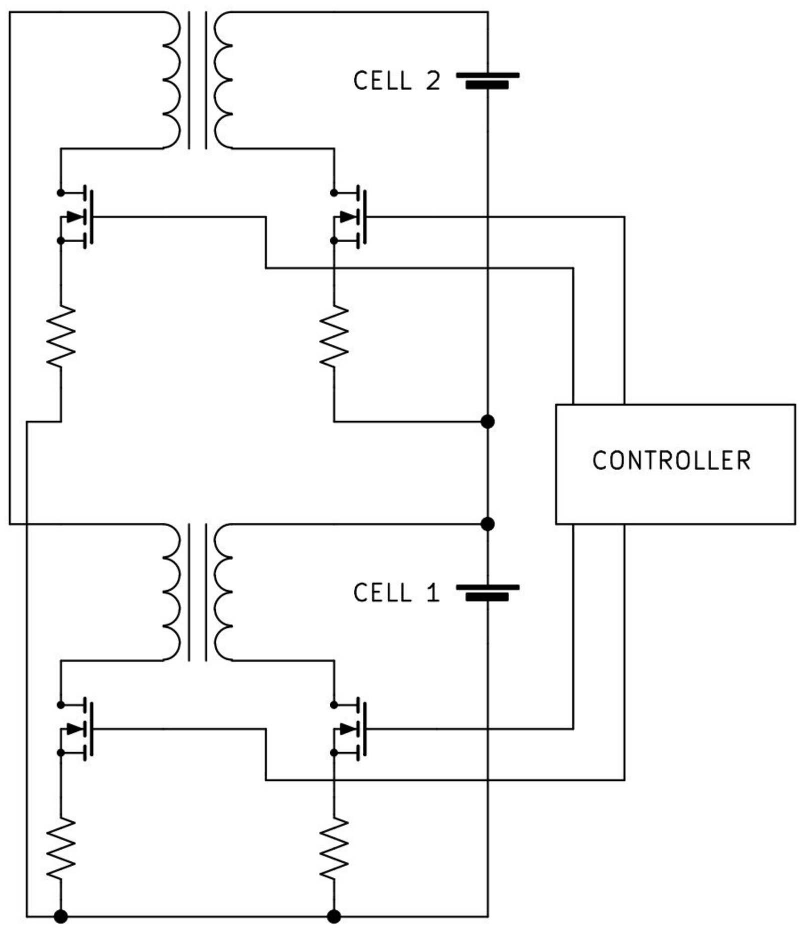


Figure 2.11: Multiple Transformer Balancer

Chapter 3

Active Bi-Directional Battery Balancing Board [13]

Active Bi-Directional Battery Balancing For Large Repurposed Lithium-ion Battery Packs

1st Walter Bartek
School of Engineering
Grand Valley State University
Grand Rapids, Michigan, USA
bartekw@mail.gvsu.edu

2nd Nicholas Baine, Ph.D., P.E.
School of Engineering
Grand Valley State University
Grand Rapids, Michigan, USA
bainen@gvsu.edu

***Abstract*—As the number of electric vehicles (EVs) increases, the number of used battery packs that require disposal increases; however, many of these packs still have useful capacity and can be repurposed. When using repurposed large lithium-ion battery packs, deviations between cells within a pack become problematic. These deviations result in a pack that is unbalanced, affecting performance and proving potentially hazardous when charging. Consequently, a battery management system (BMS) is needed. To provide safety, the BMS in this paper monitors and controls the operation of the battery pack. In addition, it controls the redistribution of charge between the cells within the pack, providing battery balancing and performance benefits. The design is tested on a repurposed battery packs. The results and performance are compared between the BMS with and without active balancing.**

I. Introduction

FROM power tools to cell phones to electric vehicles(EVs), the use of Lithium-ion batteries is increasing. While some of these use cases only require one cell, high power applications require many cells placed in series. EVs are one such high power application. To make a high-voltage battery pack, a large number of cells are connected in series and parallel groups. A Tesla Model S can have as many as 8,256 cells in its battery pack. When new, these cells exhibit very similar characteristics: capacity, open circuit voltage, self-discharge, internal resistance, et cetera. This means there is a uniformity to the pack when new; however, as the number of charge-discharge cycles experienced by the cells increases, the pack loses its uniformity. As uniformity is lost and the characteristics of individual cells deviate from one another, there is a deterioration in pack characteristics. Not only does this deterioration negatively affect the performance of the pack, the loss of uniformity in a pack increases the likelihood of a catastrophic failure.

As batteries age, battery balancing and monitoring is used to compensate for the effect of non-uniform deterioration, but it has its limitations. Eventually, a battery pack will no longer be able to perform as required for its application in an EV. At this point, the cells on average exhibit 70% of the capacity of new cells. These cells can be repurposed for less demanding applications, but often the battery management and monitoring for the pack was done by systems integrated in to the vehicle the batteries are removed from. As a result any repurposing requires a replacement battery management system. [1]

When designing a replacement battery management system, it is important to recognize that each cell in a battery pack contains a unique set of chemical and mechanical imperfections. These imperfections cause deviations from the nominal specification in each cell; this is especially true with heavily used cells. As a result, each cell in a battery pack has a slightly different behavior when compared to the other cells in the pack. As a pack goes through charge-discharge cycles, the deviation of each cell increases, and an individual cell is no longer only slightly different from the other cells. As these deviations from nominal increase, there is a decline in the performance of the pack. This is observed mainly as a decrease in the capacity of the pack. [2] When compared to other battery chemistries, lithium-ion has several advantages [1]:

- High energy density
- Low self discharge
- Low maintenance
- High charge transfer capabilities

With these advantages, though, comes the disadvantage that Lithium-ion is generally more volatile and less tolerant to operating outside its specified safe operating range. Because of this, it is imperative that a battery management system be used on lithium-ion battery packs to keep them operating within the safe operating range. As a battery pack ages and the cells deviate, more care needs to be taken to insure that all of the cells within the pack operate within their safe operating range. [1], [2]

II. Description and Purpose

With the knowledge that operating a cell outside of its intended range is damaging to the cell and dangerous, it can be seen why there is a need for a system that can help to manage the cells of a battery and keep them within their safe operating range. This is the main function of a BMS. A BMS can also be used to make the most effective use of the energy stored in the battery. Some BMSs neglect this second part and only focus on keeping the battery's operation inside its

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safe operating area. This decision is often due to the cost and complexity of more advanced BMSs. [2]

A. Functions of a BMS

A BMS can have many different functions. Some simple BMS do nothing more than monitor the voltage of all of the series connected battery groups in a battery pack. This allows the user to observe when a battery group is being over- or under-charged. More complex BMSs monitor not only the group voltages, but they can also disconnect the load or charger when a group reaches a voltage min or a voltage max. With the aid of a balancing circuit, a BMS can even distribute charge between individual groups in the pack. To maintain safety and cell health, a BMS needs to, at a minimum, perform the following functions. [2]

- Limit cells from being charged beyond their safe upper voltage limit by removing the charge current or informing the user that the charge current needs to be removed.
- Limit cells from being drained beyond their safe lower voltage limit by removing the load or informing the user that the load needs to be removed.
- Limit the temperature the cells are subjected to through limiting charge current, limiting discharge current, applying cooling, or requesting any of these options.
- Limit the charging current from exceeding a safe value by controlling the charge current or requesting a reduction of the current.
- Limit the discharge current from exceeding a safe value by controlling the discharge current or requesting a reduction of the current.

B. Types of BMS

Different types of BMSs can be categorized based on the functions they perform. Some balancers are simplistic in function while others are complex. Several different types of BMSs will be briefly discussed: charger, regulator, monitor, meter, and balancer. Table I compares these types. [2]

Simplistic in function, the charger only charges a battery. Generally, this will be done over the entire battery, whether it is a single cell or a multi-cell pack. A charger will follow a specific profile depending on the type of battery. For a lithium-ion battery, this is constant-current constant-voltage (CCCV). This profile provides a constant current to the battery until a specific voltage is reached. Once this voltage is reached, the charger will hold the voltage constant while reducing the amount of current being supplied to the battery. [2]

A regulator bypasses the charge current when a cell is fully charged. It does this through the use of a shunt placed across a cell. This allows for the cells of a battery to balance during charging but not while discharging. If the charger sources more current than the regulator can shunt, the cells or the regulator may be damaged from the excess current. If a small shunt is used, the charge current must be lowered which would prolong the charge time. To allow for quicker charging, a larger shunt would be needed, but this must be done with consideration of physical size, heat dissipation and power dissipation. [2]

TABLE I
BMS FEATURE COMPARISON

	Measure	Report	Balance	Protect During Charging	Protect During Discharging
Regulators			X		
Meters	X	X			
Monitors	X	X		X	X
Balancers	X	X	X	X	X

A meter and monitor both have the ability to measure and report parameters of a battery; however, a monitor has the additional ability to provide protection during charge and discharge by communicating with the other devices in the battery system that control the battery. [2]

A balancer is able to balance the cells within a pack. There are many different ways to balance a battery pack, some of which are discussed in the following section. [2]

C. Balancer Topologies: Dissipative and Non-Dissipative

There are two categories in which balancing topologies will be placed for the remainder of this paper: dissipative and non-dissipative. Dissipative topologies use a resistive load to burn off excess charge through thermal energy. Non-dissipative topologies, on the other hand, attempt to make use of all of the charge in a battery by shuttling charge between cells or between a cell and groups of cells. [3], [4]

Two specific balancer designs were chosen as the focus of this paper: an analog dissipative balancer and a multiple transformer balancer. Figure 2 shows an analog dissipative balancer for two cells. A transistor is placed parallel to a cell. This transistor is controller by a comparator circuit with feedback. The comparator circuit uses a voltage reference and a dividing network for its inputs. Once the voltage from the dividing network reaches that of the voltage reference, the comparator turns the transistor on. This shunts the current from the charger past the cell. As the current is shunted through the transistor, the current through the cell is lessened. This allows the voltage of the cell to be reduced as there is less of a voltage drop caused by the internal resistance of the cell. This drop in voltage is seen by the comparator, and the transistor is turned off.

Figure 3 shows a multiple transformer balancing circuit. There is a transformer for each cell in the pack. The primary of each transfomer is placed across a single cell, and the secondary of all the transformers is placed across a group of cells, sometimes even the entire pack. This allows each cell to send charge to the other cells its transformer is attached to. It also allows each cell to receive charge from the other cells its transformer is attached to. There is a variation of this design that uses a single transformer with multiple windings.

Both of these topologies were built and underwent preliminary testing. After preliminary testing, it was decided that the analog dissipative balancer would not be further explored and the focus would move to the multiple transformer balancer design. Here are some observations seen during preliminary testing of the analog dissipative balancer:

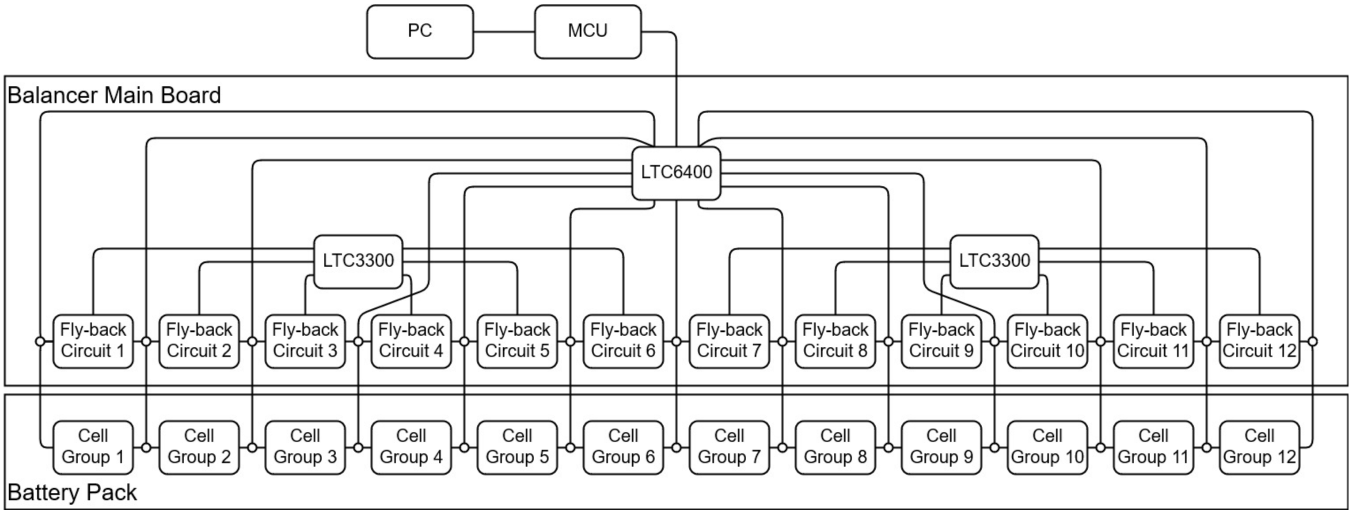

Fig. 1. Balancer Board Function Diagram

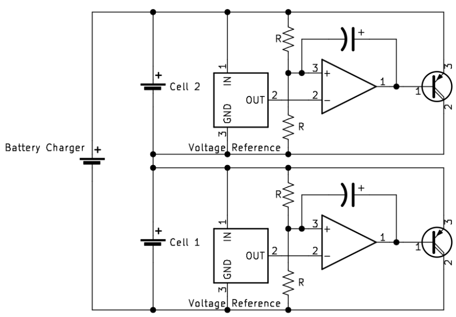

Fig. 2. An analog dissipative balancing circuit

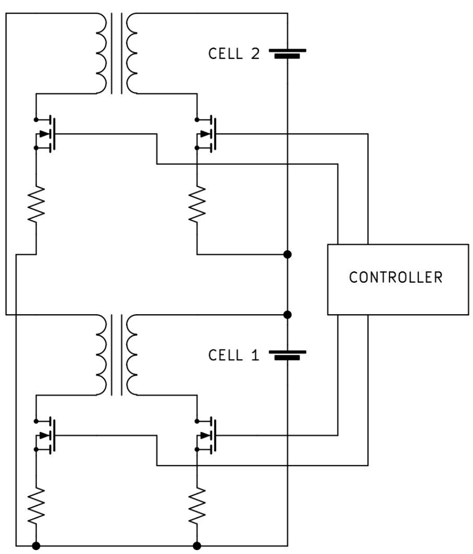

Fig. 3. A mutliple transformer balancing circuit

- In order to shunt a large charge current, transistors are needed in place of resistors. This increases complexity, cost, and temperature.
- When using transistors to shunt a large amount of current, proper cooling must be used. For testing, large passive heat-sinks were used. This cooling adds size, complexity, and cost to the balancer.
- Even with the large transistors and proper cooling, the balancer was only able to handle around 10A of current.
- As the balancer is passive and does not use a MCU, potentiometers are needed to dial in the proper shunting points for the circuit.

III. Specification and Design

A. Repurposed Battery Packs

After a pack degrades to the point of holding 70-80% designed capacity, it is no longer usable in an application such as an EV. Presently, the main method of disposal of end of life EV packs is recycling. While recycling is a better alternative than simply being disposed of in a landfill, a pack with 70-80% capacity may be able to be repurposed instead as a pack for load leveling or as a pack for a less demanding type of EV such as an industrial vehicle like a fork lift.

B. Design

A non-dissipative balancer was built and tested for this paper. After researching different available designs, it was decided that a the Linear Technology DC2100B would be the basis for the balancer to be tested. This design makes use of several Linear Technology ICs specifically designed for battery balancing applications: the LTC3300-1 and the LTC6804-2. These ICs are used to implement a DC-DC fly-back transformer circuit for each cell group in the pack [5]. The fly-back transformer circuit should allow for charge transfer efficiency of up to 96% as there is little power dissipation.

Figure 1 shows a block diagram of the balancer design. A PC is used to communicate with the ATmega2560, the MCU

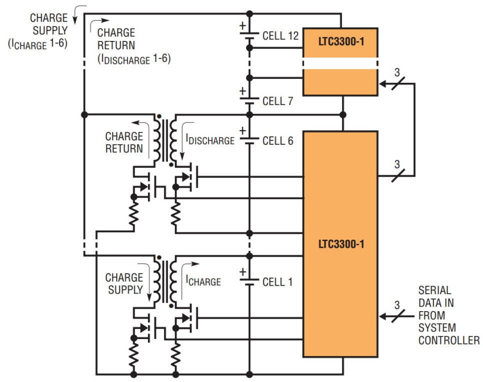

Fig. 4. A pair of LTC3300-1 connected to a twelve cell stack

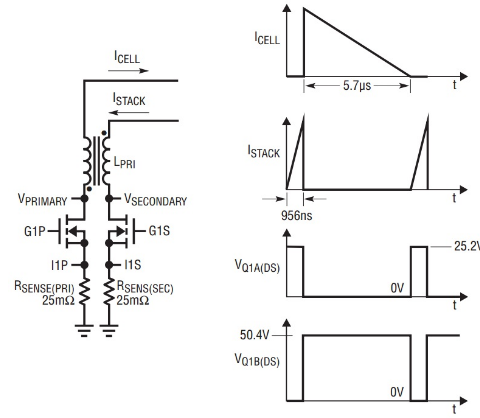

Fig. 5. Fly-back circuit charging a cell

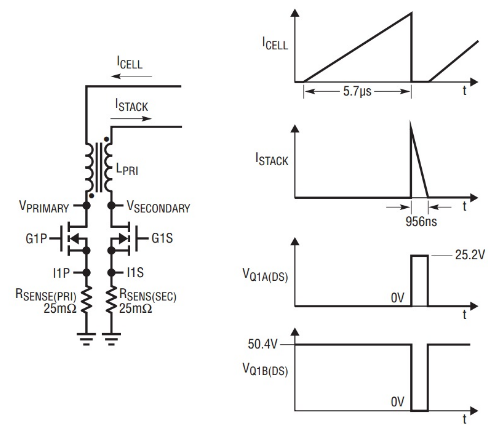

Fig. 6. Fly-back circuit discharging a cell

of the balancer. The MCU sends commands to the LTC6804. The LTC6804 measures the voltages of the twelve cell groups in the pack and also sends balancing commands to the two LTC3300s. The LTC3300s control the behavior of the fly-back transformer circuits for up to six cell groups. As indicated by the figure, the ATmega2560 is located off of the main balancer board. This allows for it to be connected to the PC more easily for communication purposes during testing.

A simplified diagram of a single fly-back circuit can be seen in Fig. 4. This figure shows the LTC3300 being used to control the fly-back transformers through the use of transistors. This design allows a group of cells to supply charge to an individual cell and also allows for an individual cell to supply charge to that same group of cells. Being able to transfer charge in this manner means that this design allows for bi-directional balancing in the pack. Figures 5 and 6 show the charge and discharge of a single cell in the pack.

Each LTC3300 is able to control up to six fly-back transformer circuits. For the fly-back transformer circuit to function, the primary of the transformer is connected to a cell group while the secondary of the transformer is connected over a number of cell groups. The secondary can be connected over as many as twelve cell groups but must share the ground of the LTC3300 for which the circuits primary is connected. This means that the secondary of the transformers connected to cells 1-6 may be connected over cells 1-6 or 1-12 but may not be connected over cells 2-12 as the ground must be connected to the cell with the lowest potential being controlled by the LTC3300. This also means that the secondary of the transformers connected to cells 7-12 may be connected over cells 7-12 but not over cells 6-12 as the ground for the LTC3300 controlling cells 7-12 is connected to the negative terminal of cell 7. [6]

IV. Testing: Plan and Results

To measure the potential of this balancer design on large repurposed battery packs, the balancing board was tested using repurposed battery packs from hybrid mass-transit buses. The pack configuration was 12s8p, 12 serial groups of 8 parallel cells. The cells that make up the packs are A123 Systems ANR26650M1-B. Each cell has a nominal voltage of 3.3VDC and a nominal capacity of 2.5Ah [7]. This gives a 12s8p pack a nominal voltage of 39.6VDC and a nominal capacity of 20Ah. To perform the tests, a high powered battery testing station was used. The testing station consisted of a computer controlled load, voltage sensors, and current sensors. Having a computer controlled load, the testing station was able to repeatably provide a set charge-discharge profile to the battery pack. A specific charge-discharge profile, as provided by the battery pack manufacturer A123 Systems, was used to test the capacity of the battery pack with and without the balancer functioning.

The capacity test profile is defined by several sections: charge, settle, discharge, settle, and charge. As seen in Figure 8, the capacity test starts with the load current being set to a charge current of 40A. For a new pack the 40A charge current would only equate to 2C as nominal pack capacity is 20Ah, but in a used pack with half of the nominal capacity, the 40A charge current is 4C. As the pack is charging, the battery test station measures individual cell voltages and compares these measured values to a set cell voltage maximum. Once a single cell reaches this set voltage maximum, the charging current is cut. The charge current steps down as follows: 40A, 30A, 20A,

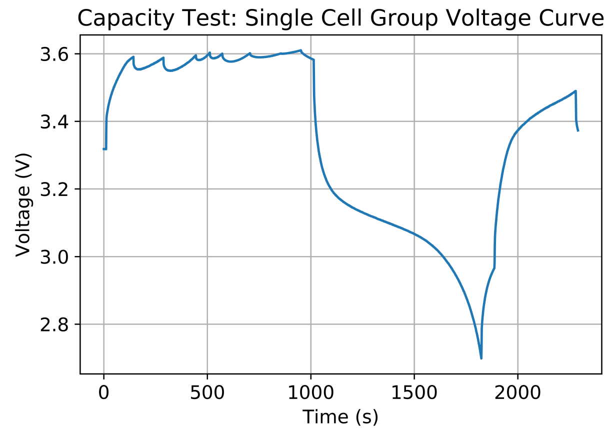

Fig. 7. The voltage curve of a single battery group as measured by the battery test station during a capacity test

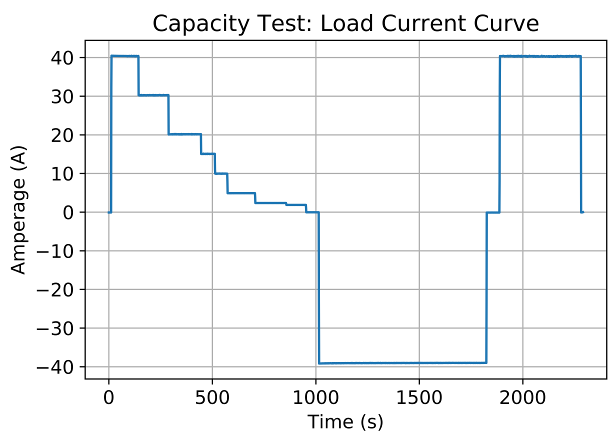

Fig. 8. The load current curve applied to the battery pack as measured by the battery test station during a capacity test

15A, 10A, 5A, 2.5A, 2A, 0A. After reaching 0A, the battery test station holds the current at 0A for a minute to allow the battery pack to settle after being charged. Once settled for a minute, the battery test station sets a discharge current of 40A. Now, the battery test tower monitors the individual cell voltages and compares these measured values to a set cell voltage minimum. When one cell reaches this voltage minimum, the battery test station cuts the discharge current to 0A. The battery test station again lets the battery pack settle with no current for a minute. With charge-discharge portion of the test done, the capacity is known. The battery test station now charges the battery pack up to half of its capacity at a current of 40A. This test profile was used for each test performed. An example curve of the load current provided by the battery test station can be seen in Figure 8; however, the duration of charging at each current will differ based on the capacity of the battery pack. The effects of the load current on an individual cell group voltages in the battery pack can be seen in Figure 7.

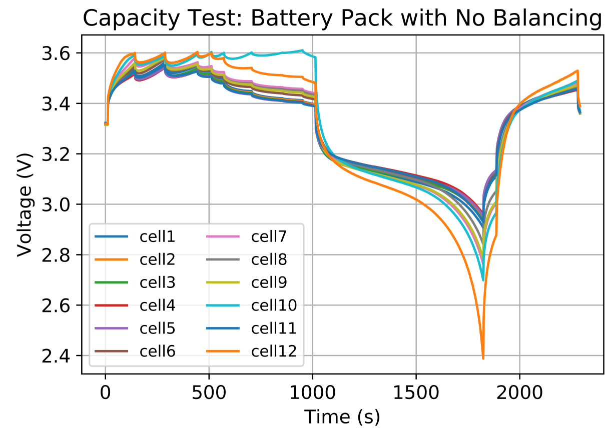

Fig. 9. Battery Pack 1 cell group voltages as measured during a capacity test with no balancing

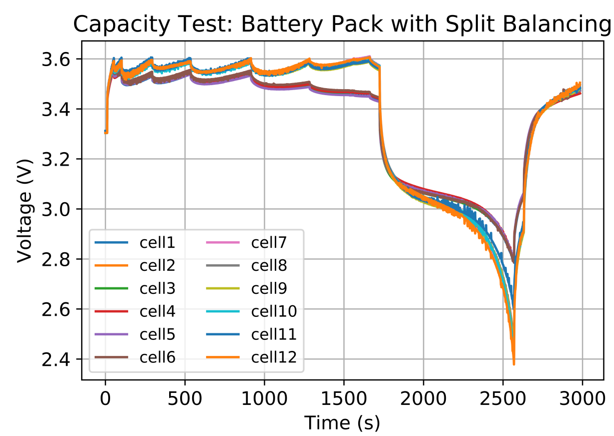

Fig. 10. Battery Pack 1 cell group voltages as measured during a capacity test with full pack balancing

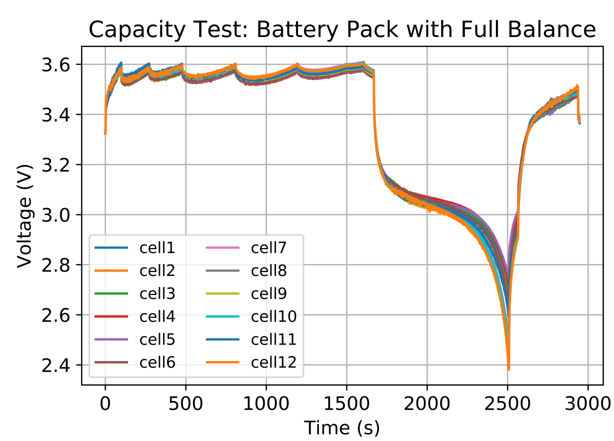

Fig. 11. Battery Pack 1 cell group voltages as measured during a capacity test with split pack balancing

A capacity test was done on the battery pack with the battery balancer disabled. The voltage measurements of the

TABLE II
BATTERY CAPACITY OF PACK 1 FOR MULTIPLE BALANCING CONFIGURATIONS AS MEASURED BY THE BATTERY TEST STATION DURING A CAPACITY TEST

	Ah	Change in Ah	Percent Change
No Balancing	8.782	-	-
Split Balancing	9.199	0.417	4.748
Full Balancing	9.563	0.781	8.893

TABLE III
BATTERY CAPACITY OF PACKS 1-4 WITH AND WITHOUT FULL-BALANCING AS MEASURED BY THE BATTERY TEST STATION DURING A CAPACITY TEST

	Unbalanced (Ah)	Balanced (Ah)	Change in Ah	Percent Change
Pack 1	8.782	9.563	0.781	8.893
Pack 2	10.846	11.308	0.462	4.260
Pack 3	12.970	13.950	0.980	7.556
Pack 4	16.369	16.685	0.316	1.930

cell groups during this test are seen in Figure 9. It is seen in Figure 9 that during the charging portion of the test two of the cell groups deviate from the rest of the pack. These two cell groups charge to a higher voltage than the rest of the pack, limiting the amount of charge the rest of the pack is able to receive. It is also seen in the figure that the two cell groups that deviated during charging are also the two cell groups that deviate the most during discharge. These two cell groups are in effect limiting how much capacity the rest of the pack is able to use.

With the baseline capacity test done, a capacity test is performed with the balancer configured to balance the top and bottom six cell groups separately. This means that the secondary of the transformers connected to cells 1-6 was connected over cells 1-6 instead of cells 1-12. The cell group voltage measurements for this test are seen in Figure 10. It is seen in the figure that, as opposed to the test with no balancing, there are two groupings of cells during charge and discharge. As in the test with no balancing, some of the cell groups charged and discharged faster than the others and limited the capacity of the pack.

Another capacity test was performed with the balancer configured to balance over all twelve cell groups. The cell group voltage measurements for this test are seen in Figure 11. As opposed to the other capacity tests, it is seen that no one cell group or group of cell groups deviates from the rest of the pack significantly during the charge and discharge sections of the test. This allows all of the cell groups to reach a higher state of charge and to reach a higher depth of discharge on average.

As seen in Table II, there is an improvement in each case that the balancer was used. The improvements for these cases were 4.748% and 8.893%. It can be seen that there is less of an improvement when the balancer was balancing cells 1-6 and cells 7-12 separately instead of all together.

Table III shows the balancing results of several more packs. These tests were done with the balancer connected over the whole pack and not split between top and bottom cell groups. It can be seen that there is an improvement when using the balancer for all cases; however, there is not a consistent amount of improvement when using the balancer. Factors, such as the condition of the pack, affected the performance of the balancer on the different battery packs.

V. CONCLUSION

In conclusion, a BMS is a must have for a repurposed battery pack. As it was seen, some cell groups in a repurposed battery back will charge and discharge faster than the rest of the battery pack. This difference in charge rate not only affects the capacity of the battery pack but poses a danger, as lithium-ion cells are highly volatile when experiencing overvoltage conditions. While a BMS is a must have, a BMS with balancing functionality is not required when using a repurposed battery pack. It has been shown that a balancing BMS is able to increase the usable capacity of a repurposed battery pack. Though increased capacity is desirable, the increase in capacity may not warrant the cost of the balancing feature. This would be determined by specific use case and specific battery pack; however, designers should note that working with aging repurposed cells increases the expected amount of deviation in the cells as the repurposed pack ages. As the results demonstrated, the BMS presented in this paper serves the purpose of managing the cells of a repurposed battery pack, controlling the charging of cells and actively balancing the pack improving the effective capacity significantly.

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Chapter 4

Extended Methodology and Extended Results

As discussed in Chapter 3 [13], this thesis focused on two battery balancer topologies as a means to balance a repurposed 12s8p battery pack. Both the dissipative and non-dissipative balancers were designed to balance a 12s8p battery pack from A123 Systems that were previously used in electric hybrid buses. This pack was filled with 96 Lithium Iron Phosphate cells rated at 3.3V and 2.5Ah [8]. Global Battery Solutions in Holland, MI has a process to test and identify bad cell groups in these repurposed battery packs. Once identified, they are able to cut groups of cells out and paste them into different battery packs. Though this matches the cell blocks in the pack more closely to the rest of the battery pack, it does not fully mitigate the inconsistencies between cell groups within a pack. The balancers in this thesis were designed with these battery packs in mind. The dissipative balancer in this thesis was designed as an analog dissipative balancer, and the non-dissipative balancer was designed as a multiple transformer fly-back balancer.

4.1 Analog Dissipative Balancer

The first use case considered for these battery packs was low-power recreational vehicles, such as golf carts. For a golf cart, it was decided that the balancer should be designed to make use of the original golf cart charger. In the case of the analog dissipative balancer, this meant that the balancer needed to be able to shunt the 10A charge current provided by the original golf cart battery charger.

Based on the design constraints imposed by the charger and the repurposed battery packs, the analog dissipative balancer was designed as seen in Fig. 4.1. To accommodate the 10A current, a Darlington pair transistor was used for the shunt on each battery block. Additionally, the large amount of power being dissipated during balancing required

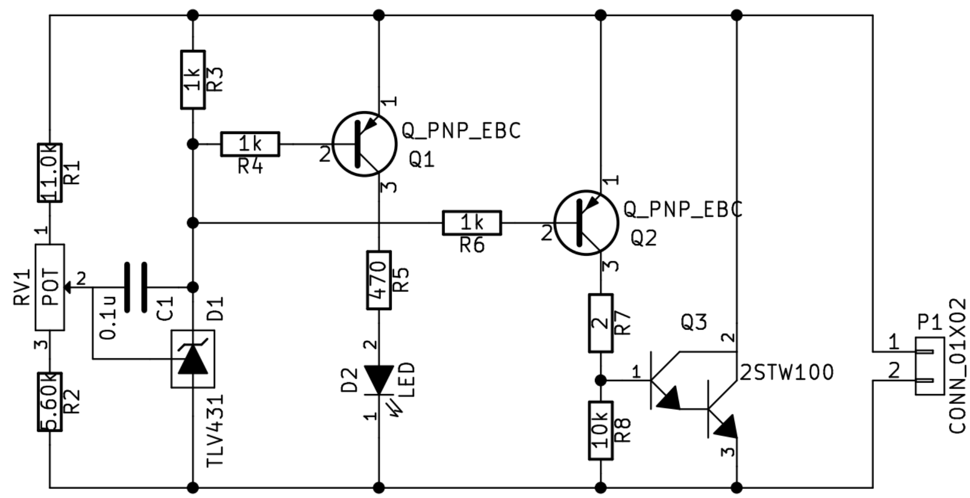


Figure 4.1: Analog Dissipative Balancer Single Cell Circuit from Prototype

that the transistors be attached to large heat sinks.

With the prototype of the analog dissipative balancer built, several test runs were conducted for the golf cart application. Tuning was required to dial in the proper cut off voltage for each cell block while balancing. Once tuned, the balancer was able to top balance the battery pack while being charged by the golf cart charger. After preliminary testing, several observations led to the decision that the analog dissipative balancer would not undergo further testing. They are as follows:

- As designed, the analog dissipative balancer was limited to a charge current of 10A.
- In order to shunt a large charge current, cooling became problematic and potentially expensive.
- Tuning of the prototype had to be done manually and a redesign would be needed to make this tuning process unnecessary, which would also increase cost and complexity.
- The time taken to balance a pack would be longer than a balancer that was balancing the during the entire charging process.
- The balancer is increasingly inefficient as the charge current increases.
- Scaling to a higher charging current requires larger transistors and more cooling, and it increases the inefficiencies.

4.2 Non-dissipative Fly-back Balancer

The design of the fly-back balancer made use of the Linear Technologies (LT) LTC 3300-1 and LTC 6804-2 control chips. The LTC 6804-2 is a ”12 Channel Multicell Battery Monitor with Addressable Interface” [14] and the LTC

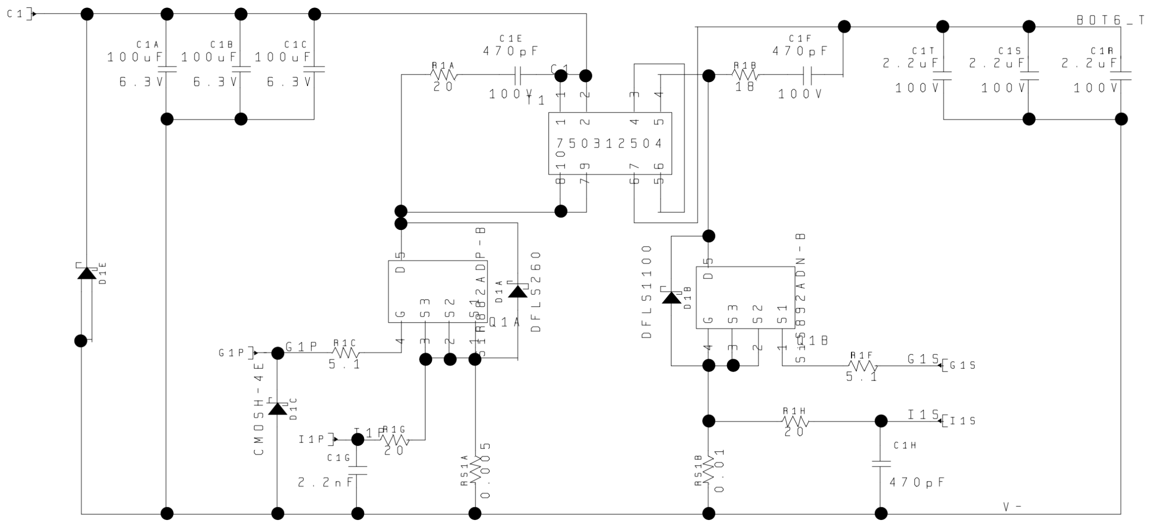


Figure 4.2: Non-Dissipative Fly-Back Balancer Single Cell Circuit

3300-1 is a "High Efficiency Bidirectional Multicell Battery Balancer " [15]. The DC2100B demo board is an example of these chips being used in their typical applications. This makes the DC2100B an excellent reference when designing with these chips. As the non-dissipative fly-back transformer did not need to shunt current during charge, the 10A charge current was not critical to the design. Instead, the application notes for the LTC3300-1, LTC6804-2, and the DC2100B were a main source of design information. As the LTC6804-2 was designed to work with up to twelve cell groups, and the LTC3300-1 was designed to work with up to six cell groups, they were a perfect fit for a design to control the repurposed 12s8p battery packs from A123 Systems.

A single fly-back circuit from the final non-dissipative fly-back balancer is shown in Fig. 4.2. The non-dissipative fly-back balancer made use of twelve of these fly-back circuits (one for each cell block) that are controlled by a pair of LTC3300-1 chips. As the LTC3300-1 controls up to six cell blocks, two chips were needed to control all twelve cell blocks. The intent of the fly-back circuit is to transfer charge between a single cell block and the entire pack and vise-versa. This is not entirely possible when using more than 6 cell blocks. Each LTC3300-1 has a lower voltage limit for the fly-back circuits that it controls. This means that the primaries of the transformers for six of the circuits are not connected over the entire pack, but instead, they are connected across the top six cell blocks. This limitation is caused by the V^- of the LTC3300-1. V^- of the LTC3300-1 needs to have the same potential as the negative leg of the primary on the transformers that it controls. The positive leg, however, is able to be at a potential that allows for up to twelve series connected cell blocks. Fig. 4.3 shows two LTC3300s connected to a pack of twelve cells with the lower LTC3300 being connected over all twelve cells. Fig. 4.4 shows a higher level view with the two possible connection styles. The first way is to connect the balancer in what will be referred to as split-pack balancing and the second way in what will be referred to as full-pack balancing, as seen in Fig. 4.4. Split-pack balancing is discussed in Section 4.2.1, and full-pack balancing is discussed in Section 4.2.2.

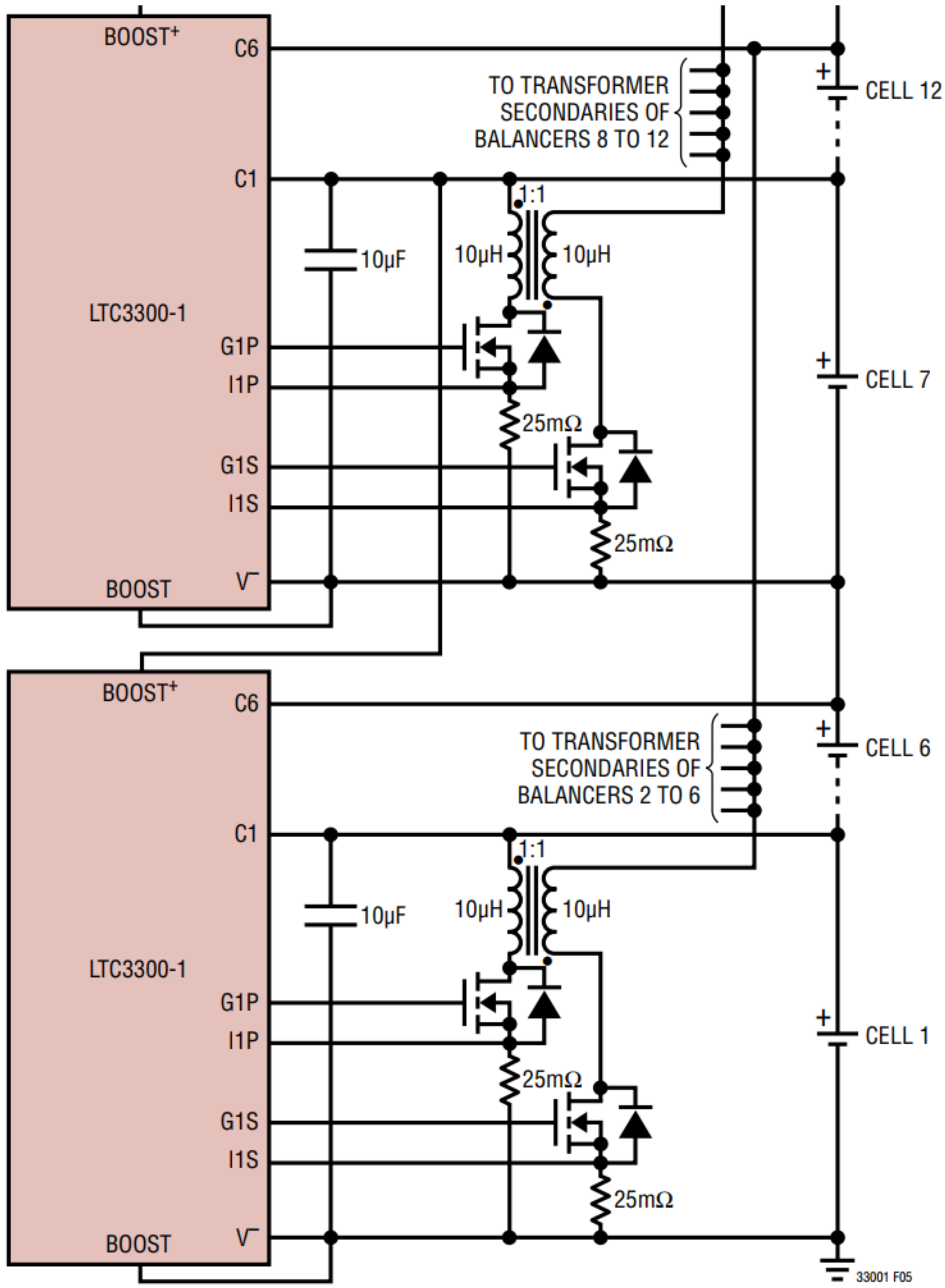
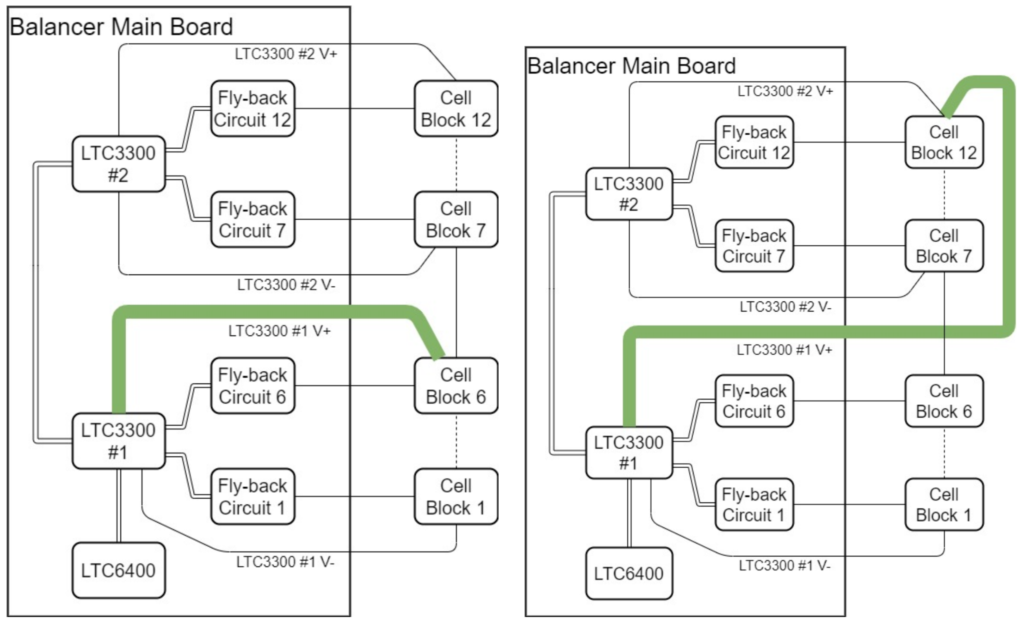


Figure 4.3: Two LTC3300 Connected Over Twelve Cells



(a) (b)

Figure 4.4: (a) Split-Pack Balancing Battery Connections (b) Full-Pack Balancing Battery Connections. In (a), it is seen that wire LTC3300 # 1 V+ is connected to the top of Cell Block 6. This allows split-pack balancing. In (b), it is seen that wire LTC300 # 1 V+ is now connected to the top of Cell Block 12. This allows full-pack balancing.

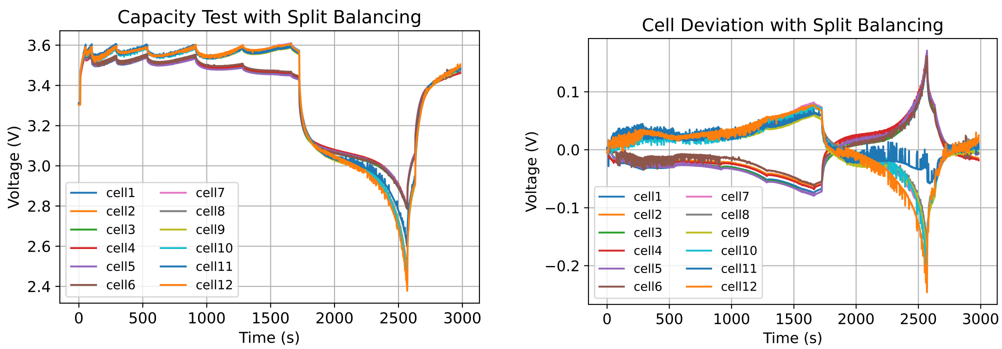
4.2.1 Split-Pack Balancing

For split-pack balancing, the primary of the transformers controlled by the LTC3300-1 over just six cell blocks. This means the fly-back circuits controlled by the first LTC3300-1 are connected over cell blocks 1-6, and the fly-back circuits controlled by the second LTC3300-1 are connected over cell blocks 7-12, as seen in Fig. 4.4a. With this configuration, the balancer is acting like a pair of six cell balancers. The results of balancing a repurposed battery pack using split-pack balancing is shown in Fig. 4.5.

As seen in Fig. 4.5a, there is a divergence between cell blocks 1-6 and cell blocks 7-12. Cell blocks 7-12 did not perform as well as cell blocks 1-6. This was due to cell blocks 7-12 having weaker cell blocks. As charge is not able to be shared between cell block groups, the group with weaker cell blocks is not able to be helped by the group with stronger cell blocks. Full-pack balancing helps solve this problem.

4.2.2 Full-Pack Balancing

For full-pack balancing, the primary of the transformers controlled by the first LTC3300-1 is now connected over the entire battery pack, instead of only the bottom six cell blocks, as seen in Fig. 4.4b. The second LTC3300-1 is still connected over the top six cell blocks. If there were more cell blocks in series above the twelve in the battery pack, the second LTC3300-1 would be able to be connected over a group of twelve cell blocks that starts with cell block 7. Fig.



(a) (b)

Figure 4.5: Capacity Test Results for Battery Pack 1. (a) voltages of series battery blocks with split-balancing applied. (b) cell voltage deviation from mean with split-balancing applied.

Table 4.1: Battery capacity of Pack 1 for multiple balancing configurations as measured by the battery test station during a capacity test

	Ah	Change in Ah	Percent Change
No Balancing	8.782	-	-
Split-Pack Balancing	9.199	0.417	4.748
Full-Pack Balancing	9.563	0.781	8.893

4.7b shows full-pack balancing on the same battery pack as the split-balancing test. Table 4.1 shows a comparison the capacity recovered by split-pack balancing and by full-pack balancing. Full-pack balancing was able to recover 0.781 compared to 0.417 by using split-pack balancing. This shows full-pack balancing to be more beneficial than split-pack balancing.

4.3 Results

Capacity tests with and without balancing were done on four repurposed battery packs. After tests were completed on the first battery pack, it was seen that split-balancing was not as effective as full-pack balancing. This was expected as charge was not able to be shared between all twelve cells. Because of this, split-balancing was not tested on the three other battery packs. Test results for Battery Packs 1, 2, 3, and 4 are shown in Fig. 4.7-4.10, respectively. Table 4.1 shows the change in capacity for Battery Pack 1 with no balancing, split-pack balancing, and full-pack balancing. Table 4.2 summarizes the change in capacity for Battery Packs 1-4 with no balancing and full-pack balancing.

4.3.1 Battery Pack 1

Battery Pack 1 started with a capacity of 8.782Ah, as seen in Table 4.2. Split-balancing was able to recover 0.417Ah. Full-pack-balancing was able to recover 0.781Ah, nearly double the capacity recovered with split-pack balancing. Fig. 4.6 indicates that Cell Blocks 10 and 12 are the weak cell blocks in Battery Pack 1 with Cell Block 10 being weaker

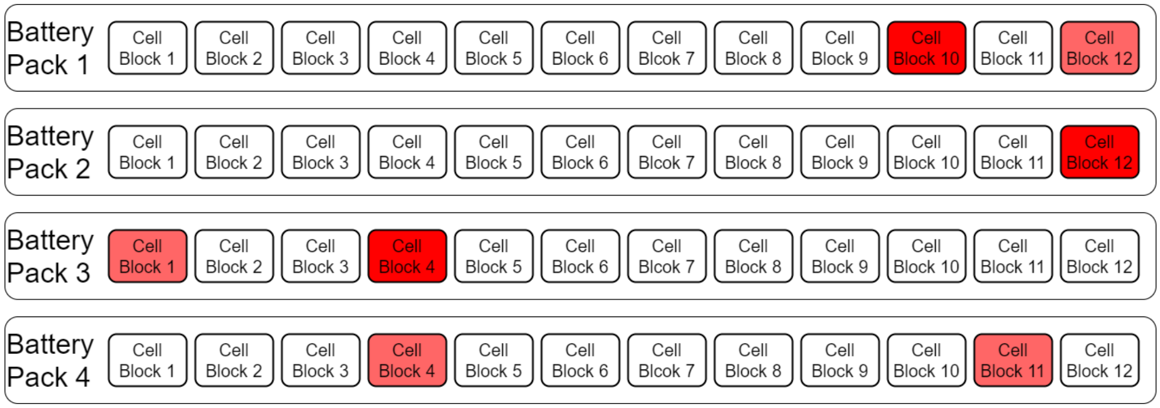
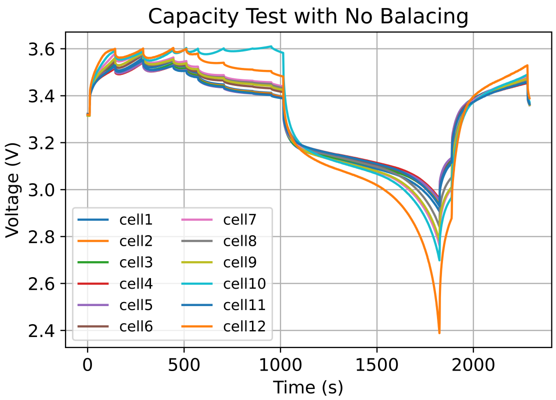


Figure 4.6: Battery Packs 1-4 Cell Block Health

than Cell Block 12. Looking at Fig. 4.7a, it is seen that the two cell blocks diverge from the rest during charge and discharge. Fig. 4.7c makes this divergence easier to see. During the charging portion of the test, the voltages of Cell Blocks 10 and 12 increase faster than the rest of the battery pack. A similar behavior is seen during discharge; the voltages of Cell Blocks 10 and 12 decrease faster than the rest of the battery pack. Looking at Fig. 4.7b, minimal cell block divergence is seen. Fig. 4.7d plots the deviation in cell block voltages from the mean. Cell blocks 10 and 12 begin to diverge as the battery pack is discharged. Comparing Fig. 4.7c and Fig. 4.7d, it is seen that the divergence with balancing is less that the divergence without. When looking at Fig. 4.7e and Fig. 4.7f, it is seen that the standard deviation (σ) of the cell block voltages during the test is higher when there is no balancing.

4.3.2 Battery Pack 2

Battery Pack 2 started with a capacity of 10.846Ah, as seen in Table 4.2. Full-pack balancing was able to recover 0.462Ah. Fig. 4.6 indicates that Cell Block 12 is the weak cell block in Battery Pack 2. Looking at Fig. 4.8a, it is seen that Cell Block 12 diverges from the rest during charge and discharge. Fig. 4.8c illustrates that divergence as a difference from the mean. During the charging portion of the test, the voltage of Cell Block 12 increases faster than the rest of the battery pack. A similar behavior is seen during discharge; the voltage of Cell Block 12 decrease faster than the rest of the battery pack. Looking at Fig. 4.8b, the Cell Block divergence is seen to be less than during the test with no balancing. Fig. 4.8d shows that during a portion of the charging test Cell Block 12 began to diverge from the rest of the battery pack but was brought back into line with the rest of the battery pack. Cell Block 12 is discharged first with balancing, as it was without, but it is seen that it does not diverge from the mean by as much when balanced. Fig. 4.8e and Fig. 4.8f show that the highest σ of cell block voltages is seen at the end of discharge. When comparing these, it can be seen that the worst σ with balancing is about half that of without balancing.



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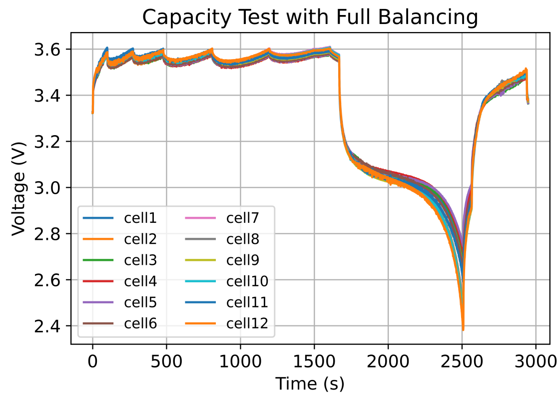

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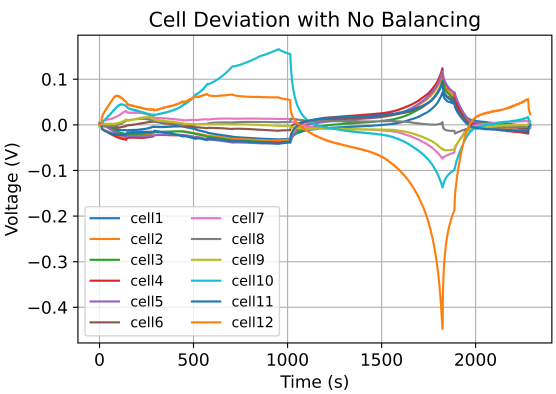

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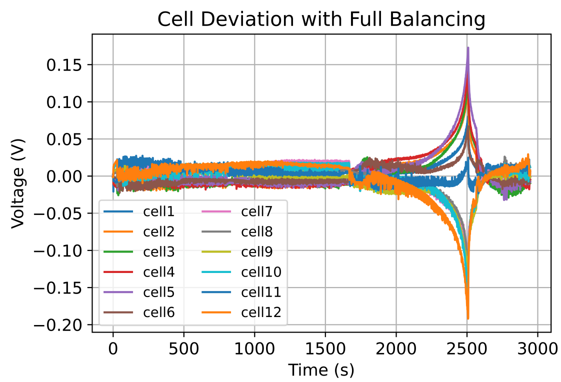

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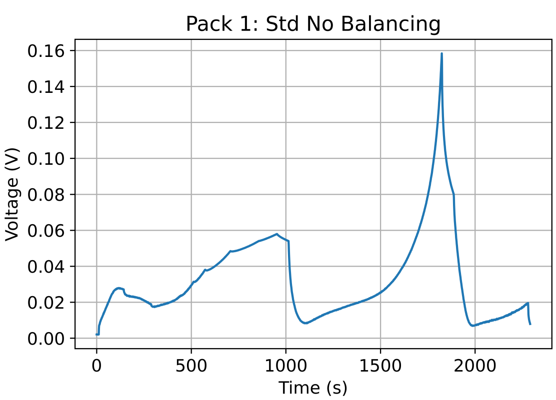

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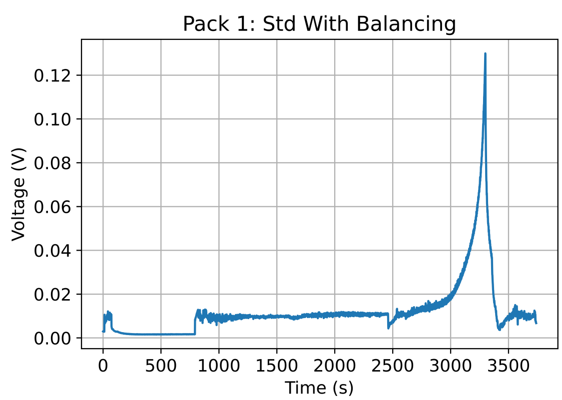
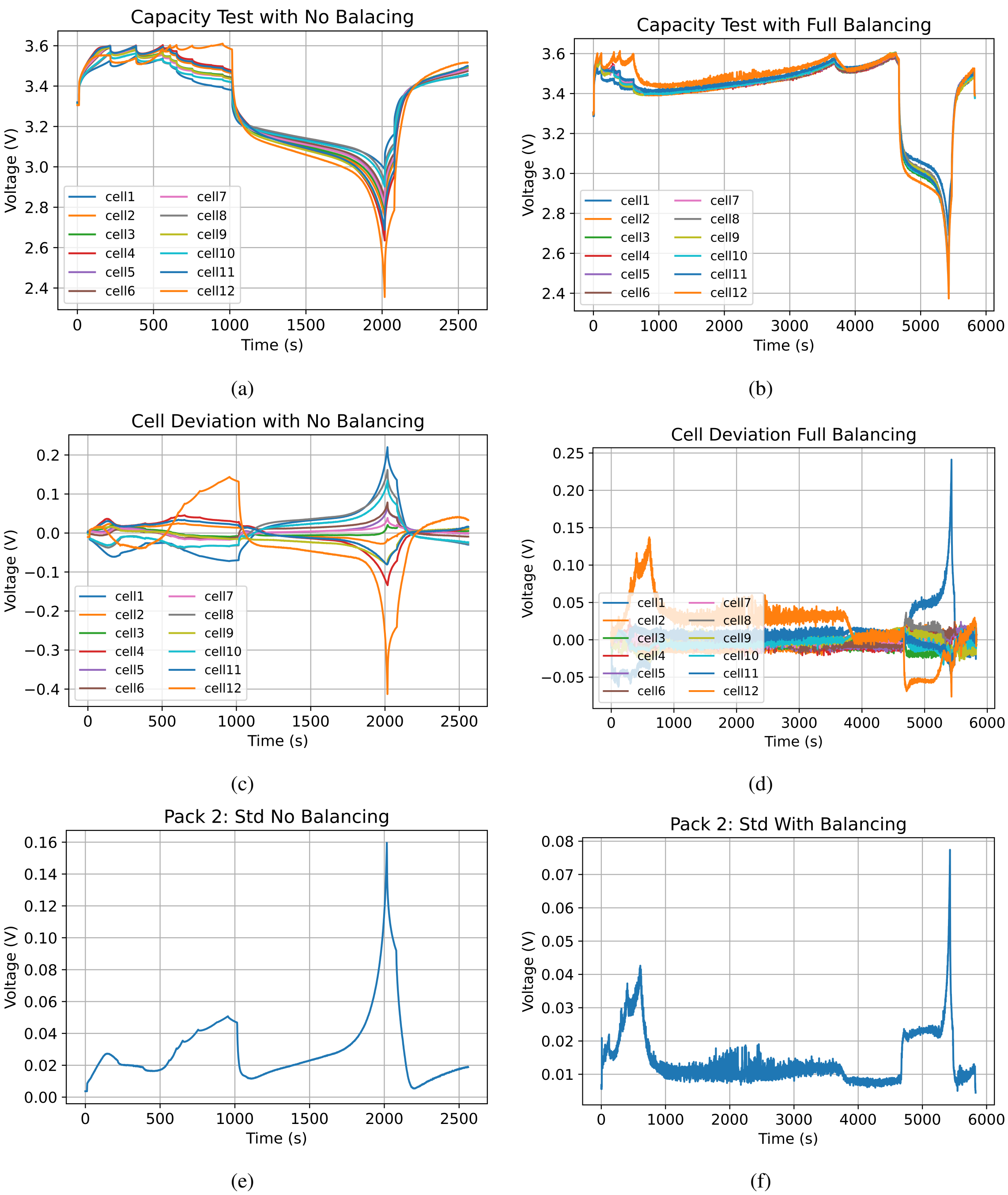


(f)

Figure 4.7: Capacity Test Results for Battery Pack 1. (a) voltages of series battery blocks with no balancing. (b) voltages of series battery blocks with full-pack balancing. (c) cell voltage deviation from mean with no balancing. (d) cell voltage deviation from mean with full-pack balancing. (e) pack σ with no balancing. (f) pack σ with full-pack balancing.



(a) (b) (c) (d) (e) (f)

Figure 4.8: Capacity Test Results for Battery Pack 2. (a) voltages of series battery blocks with no balancing applied. (b) voltages of series battery blocks with full-pack balancing applied. (c) cell voltage deviation from mean with no balancing applied. (d) cell voltage deviation from mean with full-pack balancing applied. (e) pack σ with no balancing. (f) pack σ with full-pack balancing.

Table 4.2: Battery capacity of Packs 1-4 with and without full-pack balancing as measured by the battery test station during a capacity test

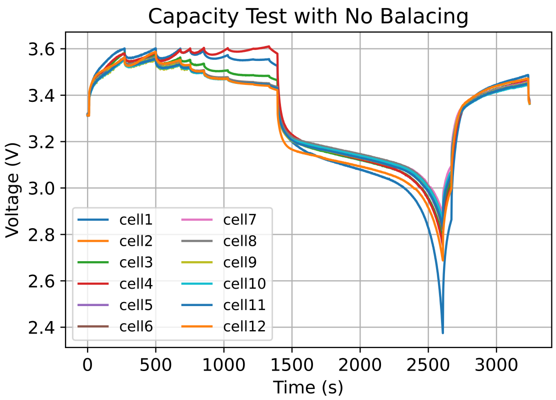
	Unbalanced (Ah)	Balanced (Ah)	Change in Ah	Percent Change
Pack 1	8.782	9.563	0.781	8.893
Pack 2	10.846	11.308	0.462	4.260
Pack 3	12.970	13.950	0.980	7.556
Pack 4	16.369	16.685	0.316	1.930

4.3.3 Battery Pack 3

Battery Pack 3 started with a capacity of 12.970Ah, as seen in Table 4.2. Full-pack balancing was able to recover 0.980Ah. Fig. 4.6 indicates that Cell Blocks 1 and 4 are the weak cells in Battery Pack 3 with Cell Block 4 being weaker than Cell Block 1. Looking at Fig. 4.9a, it is seen that Cell Blocks 1 and 4 diverge from the rest during charge and discharge. Fig. 4.9c makes it easier to see how those two cell blocks diverge. During the charging portion of the test, the voltage of Cell Block 4 increases faster than the rest of the battery pack. In the other battery packs, the cell block that was most divergent during charging was also the most divergent during discharging. This behavior is not seen in Battery Pack 3. Instead, a different cell block is divergent during charging than during discharging. Looking at Fig. 4.9b, the cell block divergence is seen to be less than during the test with no balancing. Fig. 4.9d shows that there is much less divergence from mean during balancing. Fig. 4.9e and Fig. 4.9f show that the σ is much less when the battery pack is being balanced.

4.3.4 Battery Pack 4

Battery Pack 4 started with a capacity of 16.369Ah, as seen in Table 4.2. Full-pack balancing was able to recover 0.316Ah. Fig. 4.6 indicates Cell Blocks 4 and 11 to be the weak cell blocks in Battery Pack 4. Looking at Fig. 4.10a, it is seen that Cell Block 4 diverges from the rest during charge and discharge. It is also seen that Cell Block 11 diverges during discharge. This divergence is seen as a difference from the mean in Fig. 4.10c. The voltage of Cell Block 4 increases faster than the rest of the pack during charging. During discharging, this behavior is not as prevalent. Fig. 4.10b shows the cell block divergence to be less with balancing. Fig. 4.10d shows little divergence in cell voltage during charging and only Cell Block 4 diverges from the rest of the pack at the end of discharging. When comparing the σ of the battery pack without balancing and with balancing, Fig. 4.10e and Fig. 4.10f shows less difference than was seen in the other battery packs.



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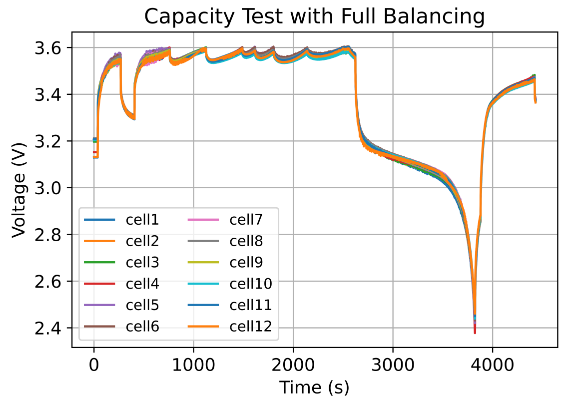

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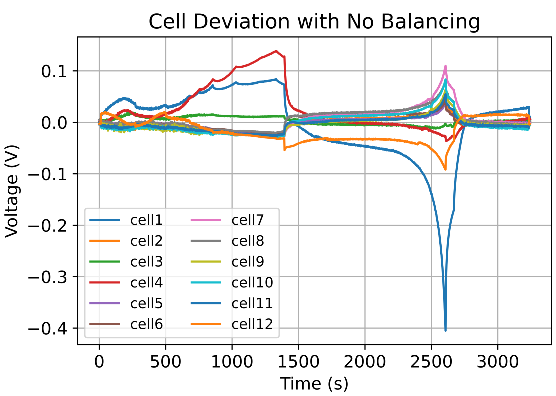

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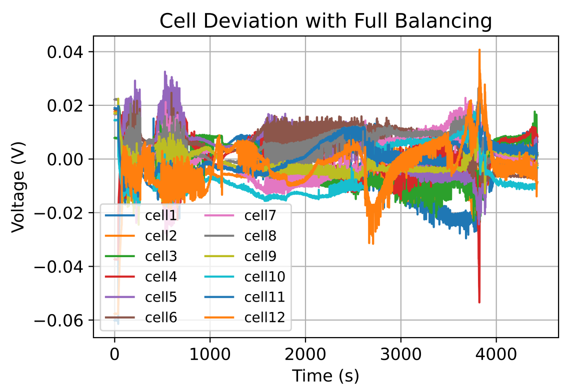

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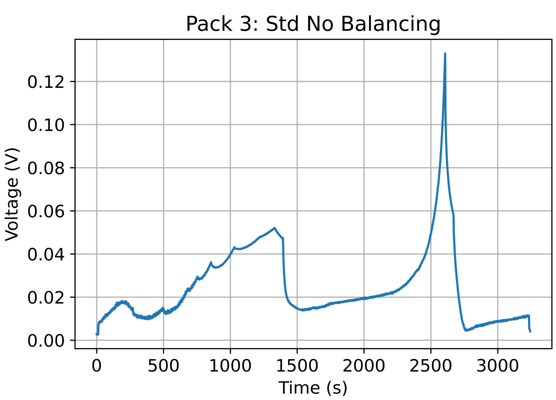

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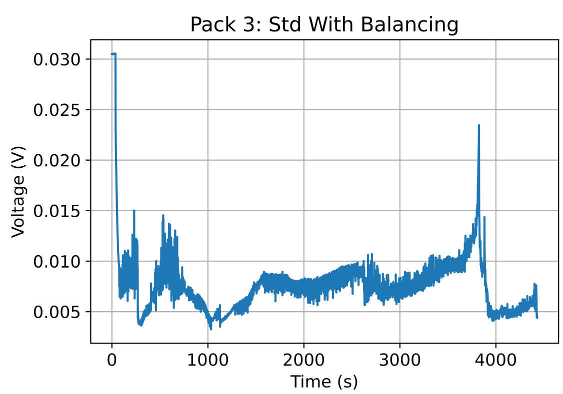

(f)

Figure 4.9: Capacity Test Results for Battery Pack 3. (a) voltages of series battery blocks with no balancing applied. (b) voltages of series battery blocks with full-pack balancing applied. (c) cell voltage deviation from mean with no balancing applied. (d) cell voltage deviation from mean with full-pack balancing applied. (e) pack σ with no balancing. (f) pack σ with full-pack balancing.

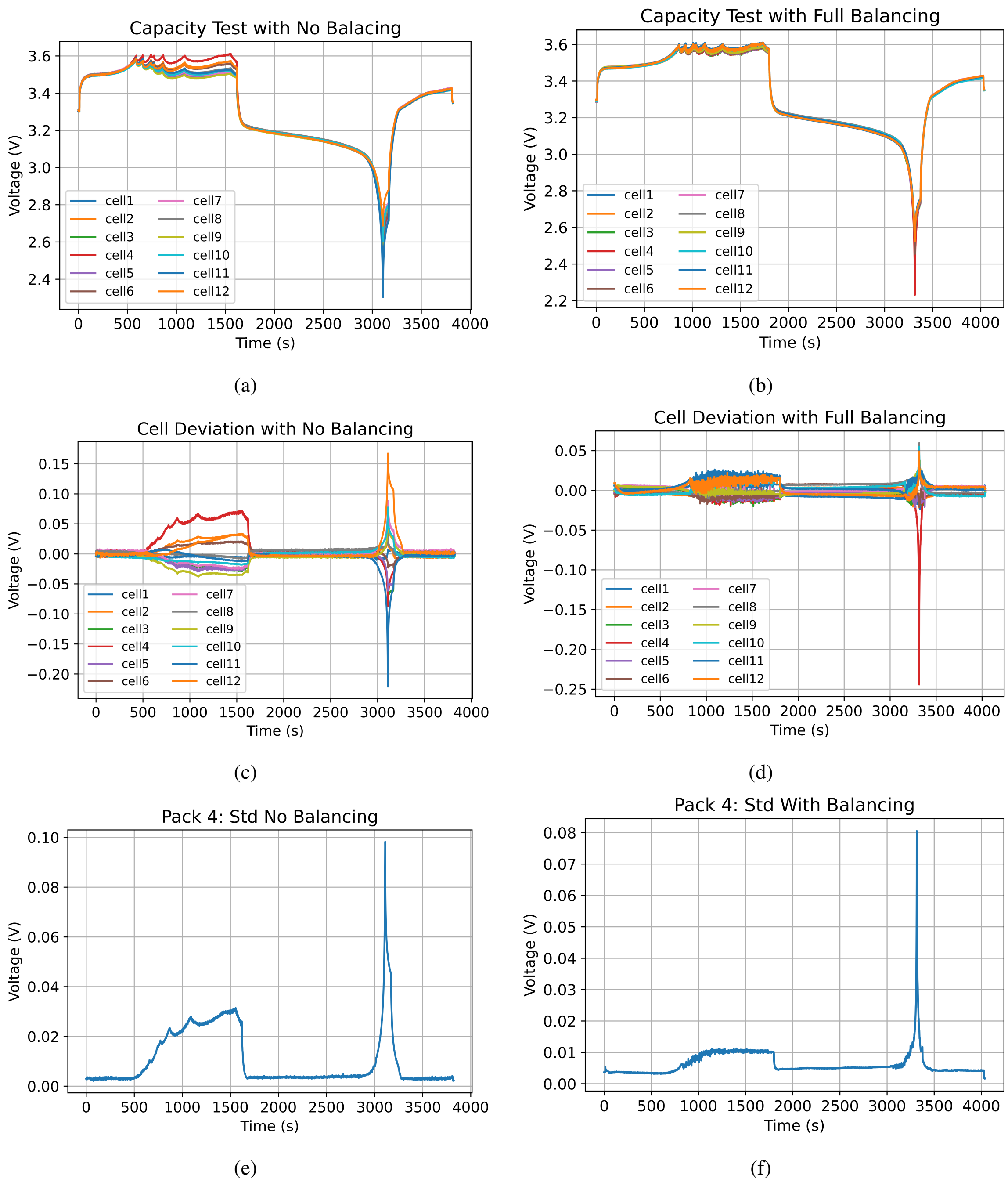

Figure 4.10: Capacity Test Results for Battery Pack 4. (a) voltages of series battery blocks with no balancing applied. (b) voltages of series battery blocks with full-pack balancing applied. (c) cell voltage deviation from mean with no balancing applied. (d) cell voltage deviation from mean with full-pack balancing applied. (e) pack σ with no balancing. (f) pack σ with full-pack balancing.

Chapter 5

Conclusion

5.1 Discussion

This thesis set out to explore the use of different balancing topologies on large repurposed lithium-ion battery packs. Two specific topologies were explored: analog dissipative and non-dissipative fly-back. Each topology was designed, and prototypes were made. The analog dissipative balancer prototype performed as expected. When connected to a golf cart battery charger, it was able to shunt the full charge current of 10A when the cells reached full charge. To do this, large heat sinks were used to cool the large transistors. While effective, the cooling required added to the size, weight, and cost of the design. The nature of the balancer is also quite wasteful as much of the energy being put out by the charger is dissipated as heat by the transistors shunting the current around fully charged cell blocks. As such, this style of balancer does not prove to be efficient in terms of size or energy in many applications, and this design scales poorly.

The non-dissipative fly-back balancer also met expectations. Unlike the analog dissipative balancer, the non-dissipative fly-back balancer did not need to shunt the charge current. Instead of converting energy into heat, as a non-dissipative balancer, the fly-back topology transfers energy to other cells. This allows for much less cooling to be used as the efficiency of the process creates much less heat. As the non-dissipative fly-back balancer is controlled by a MCU, it is able to be used on multiple different battery chemistries. This allows for more versitility than found in the analog dissipative balancer. Table 4.1 and Table 4.2 show that the balancer was able to make a percent change of up to 8.893%. They also show that for a stronger battery pack, like Battery Pack 4, the balancer makes less difference: 1.930%.

By looking at the standard deviation (σ) of cell block voltages of the battery packs, it is seen that although the charge and discharge currents used during the test were much higher than the balancing current used, the balancer was still able to keep the cell blocks close together. It can be seen that the standard deviation is consistently around 0.01V, but it is rarely smooth. This is likely due to the control algorithm allowing the cell block voltages to overshoot when attempting to bring a cell block into line with the others as it compensates for the affect the current has on the cell block voltage.

It was shown, that the worse the differentiation between cell blocks, the more benefit there is in non-dissipative balancing. This makes non-dissipative balancing more advantageous in some applications and less so in others. The non-dissipative fly-back balancer also lends itself to being scaled. Parameters for different battery types are able to be input into the firmware run on the balancer making it usable with differing chemistries. The Linear Technology chips are also able to be connected in a daisy chain with one MCU controlling the entire chain allowing for larger battery packs. Whether this improvement in capacity and versatility will justify the cost for a specific application is largely dependent upon that application.

5.2 Future Work

While it was seen that the non-dissipative fly-back balancer was able to increase the effective capacity of a repurposed battery pack by over 8%, the cost effectiveness of this solution was not explored sufficiently to make a recommendation for implementation. A cost benefit analysis of this balancer design in different applications would be useful. In some use cases, making the most effective use of charging energy may not be a top priority, and other cases may not be as affected by time to charge and can make better use of different styles of balancing that allow for lower charge currents.

The algorithm used by the non-dissipative fly-back balancer was simple. The algorithm would take a voltage measurement of the cell blocks, find the mean voltage, compare cell block voltages to the mean, and balance the cells outside a predefined deviation from the mean. While functional, this algorithm balances based on voltages which is not an ideal metric to balance. In order to maximize the energy of the battery pack a better metric would be State of Charge (SOC). To balance based on SOC, an accurate battery model is needed. As it is difficult to come up with a sufficiently accurate model, some form state estimation would be needed. A strong candidate for this would be a Kalman Filter. Being non-linear, an Extended Kalman Filter or an Unscented Kalman Filter would be reasonable choices. With a sufficiently accurate battery model, more complex algorithms can be used. There are numerous way to optimize the controller which should be based on the application the balancer would be used in.

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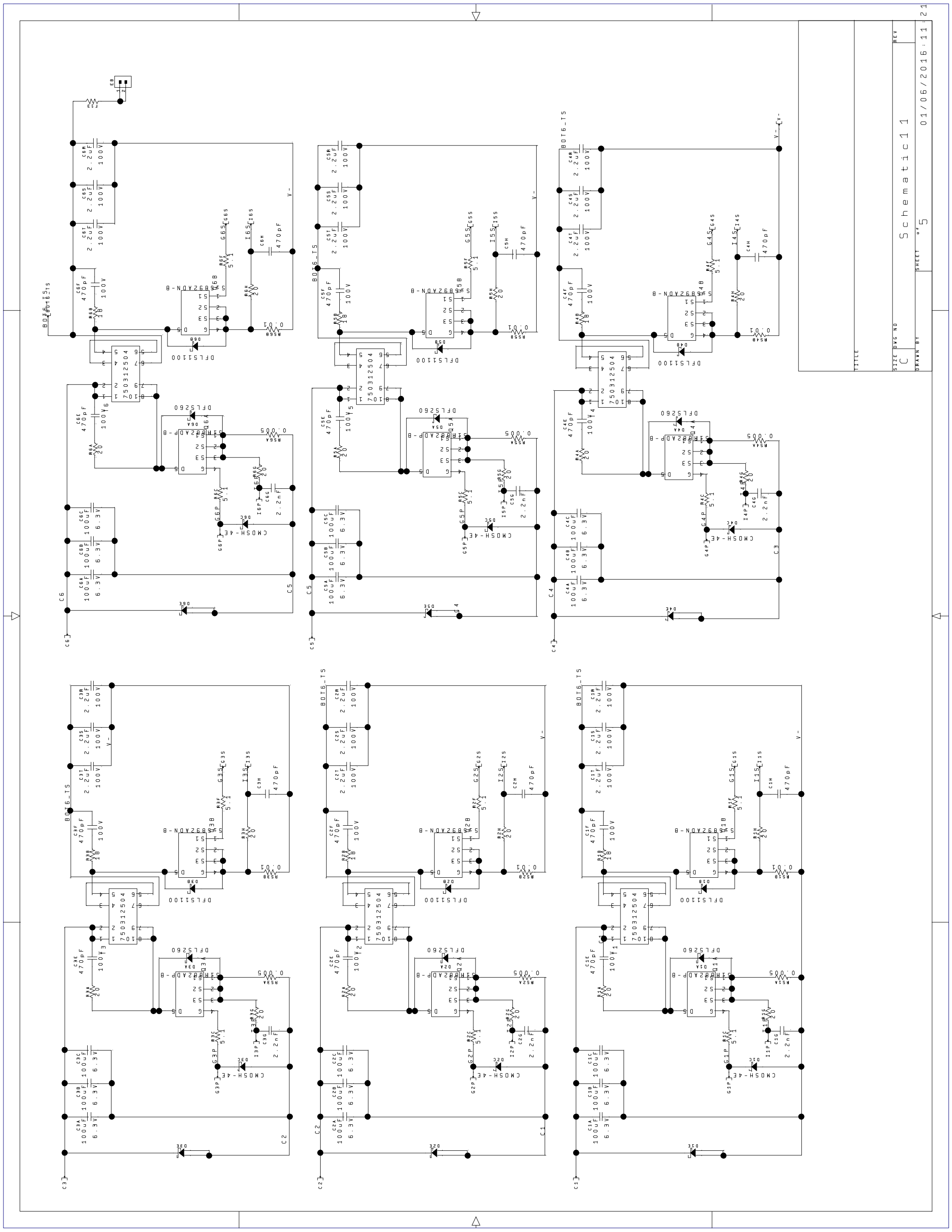
A Non-Dissipative Fly-Back Balancer Schematic 1



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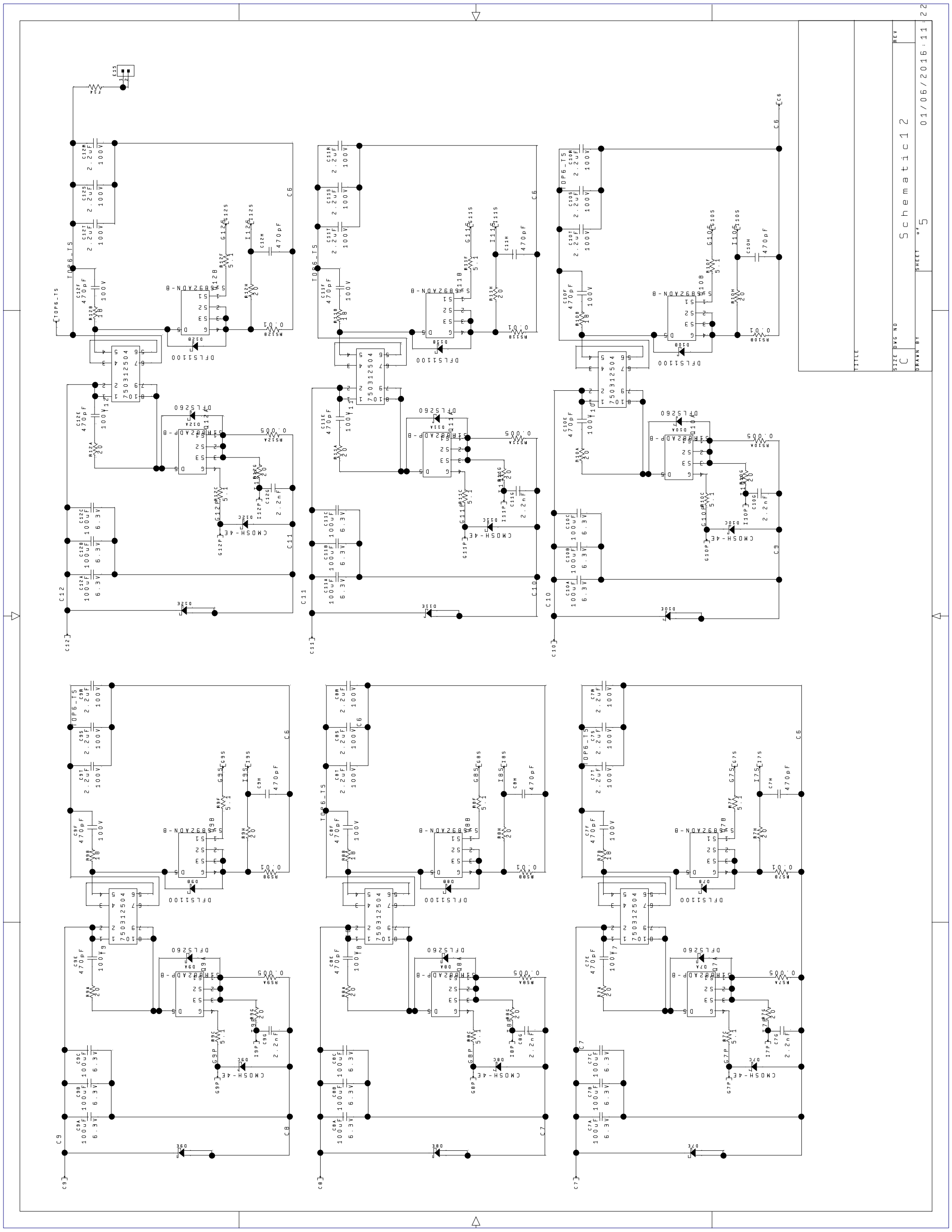

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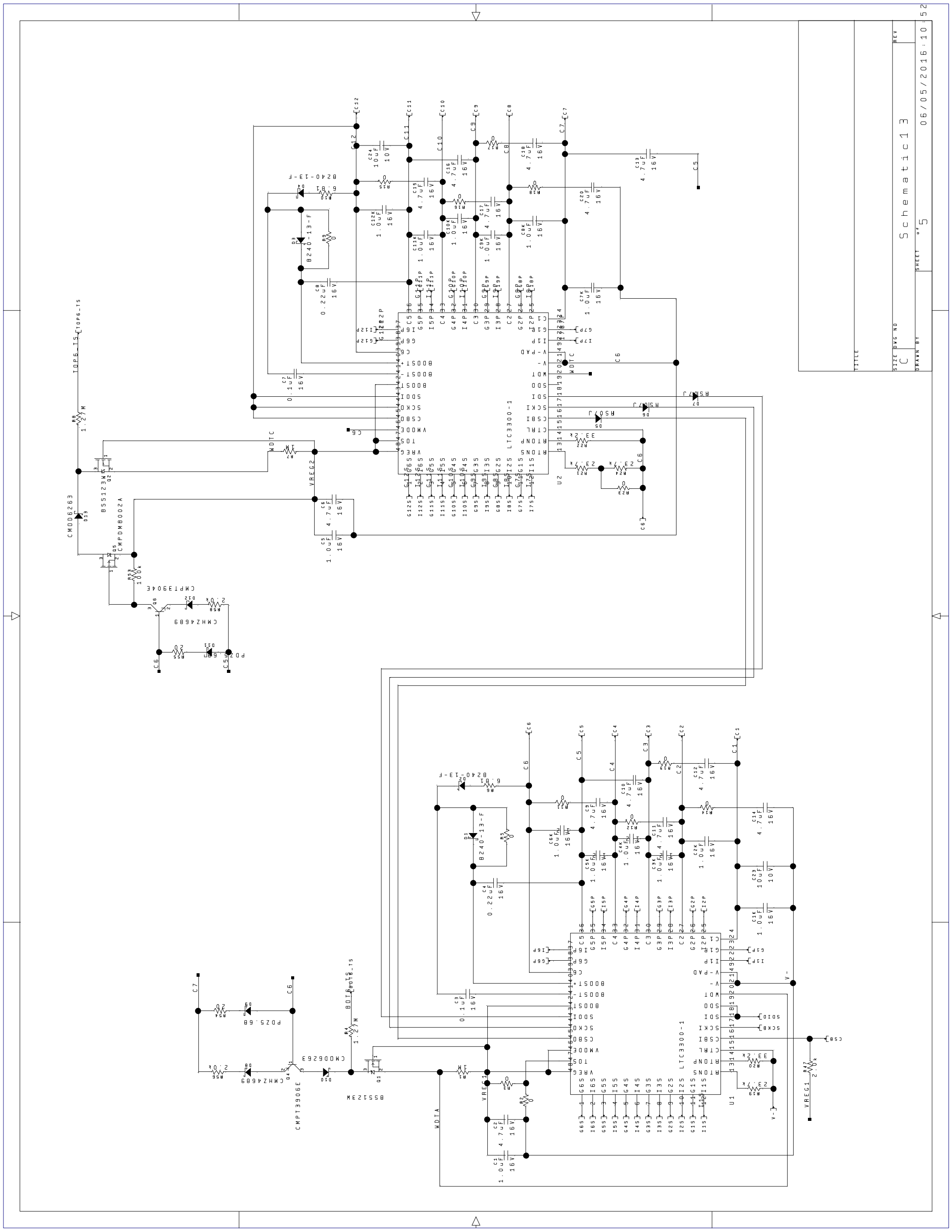

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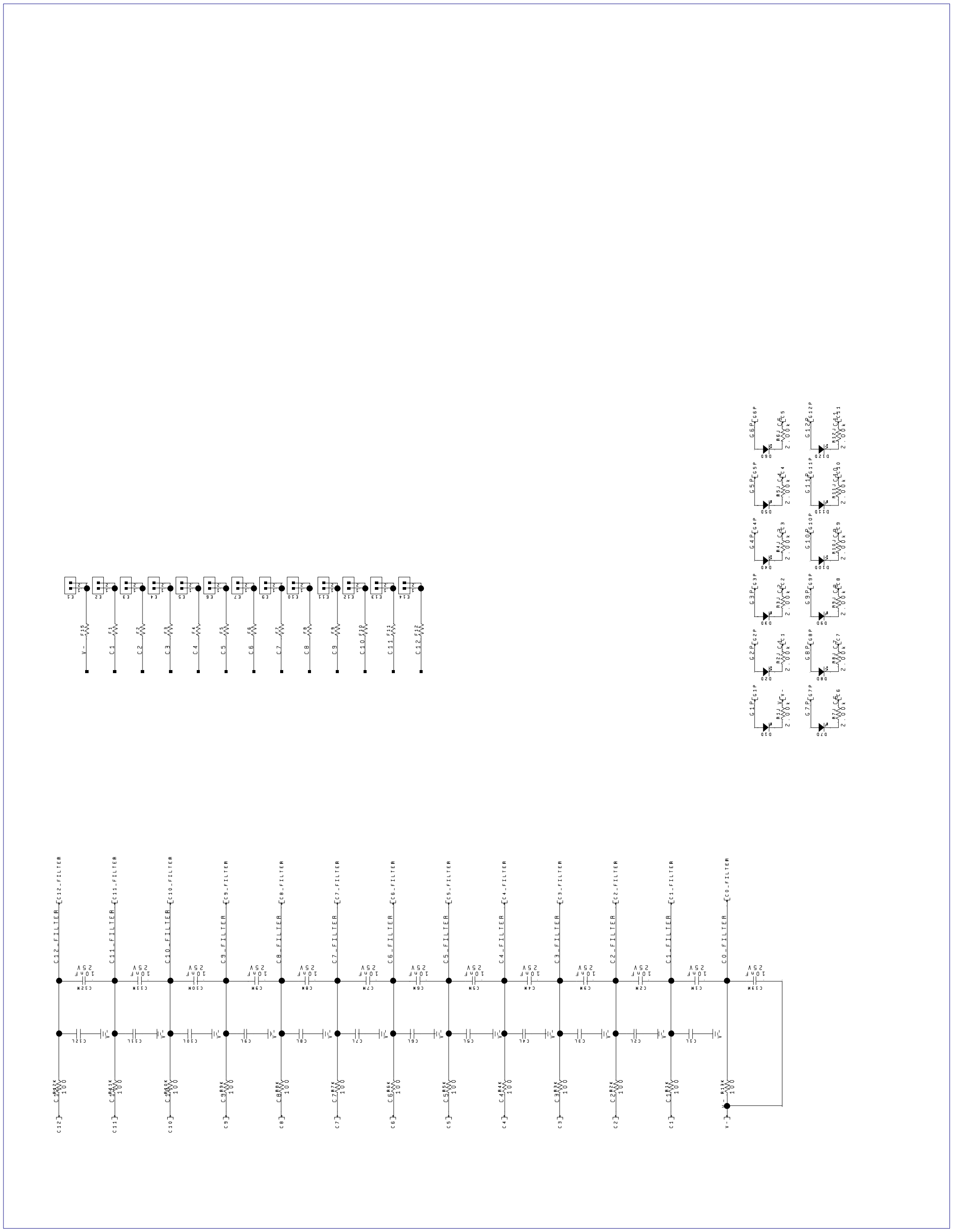

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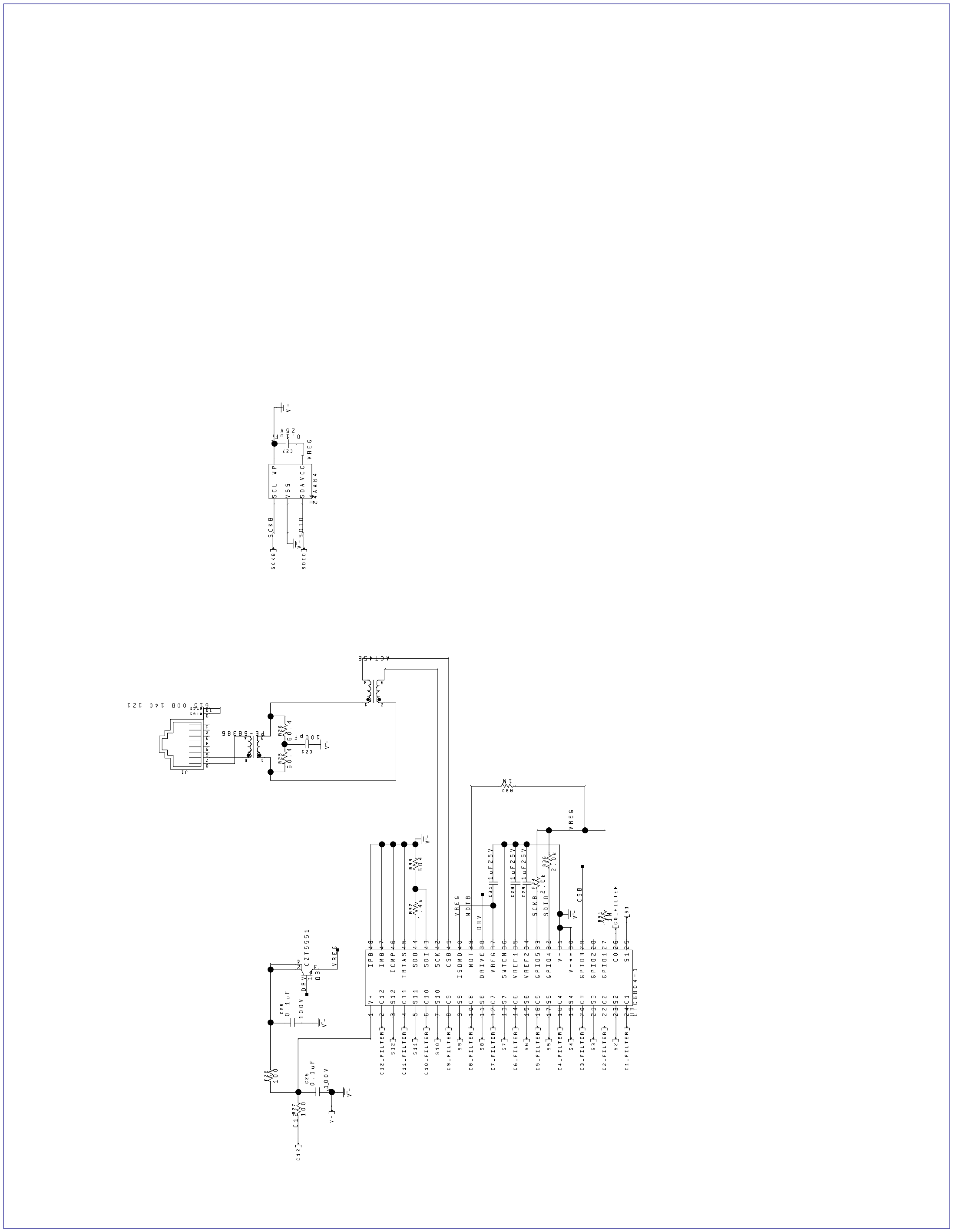

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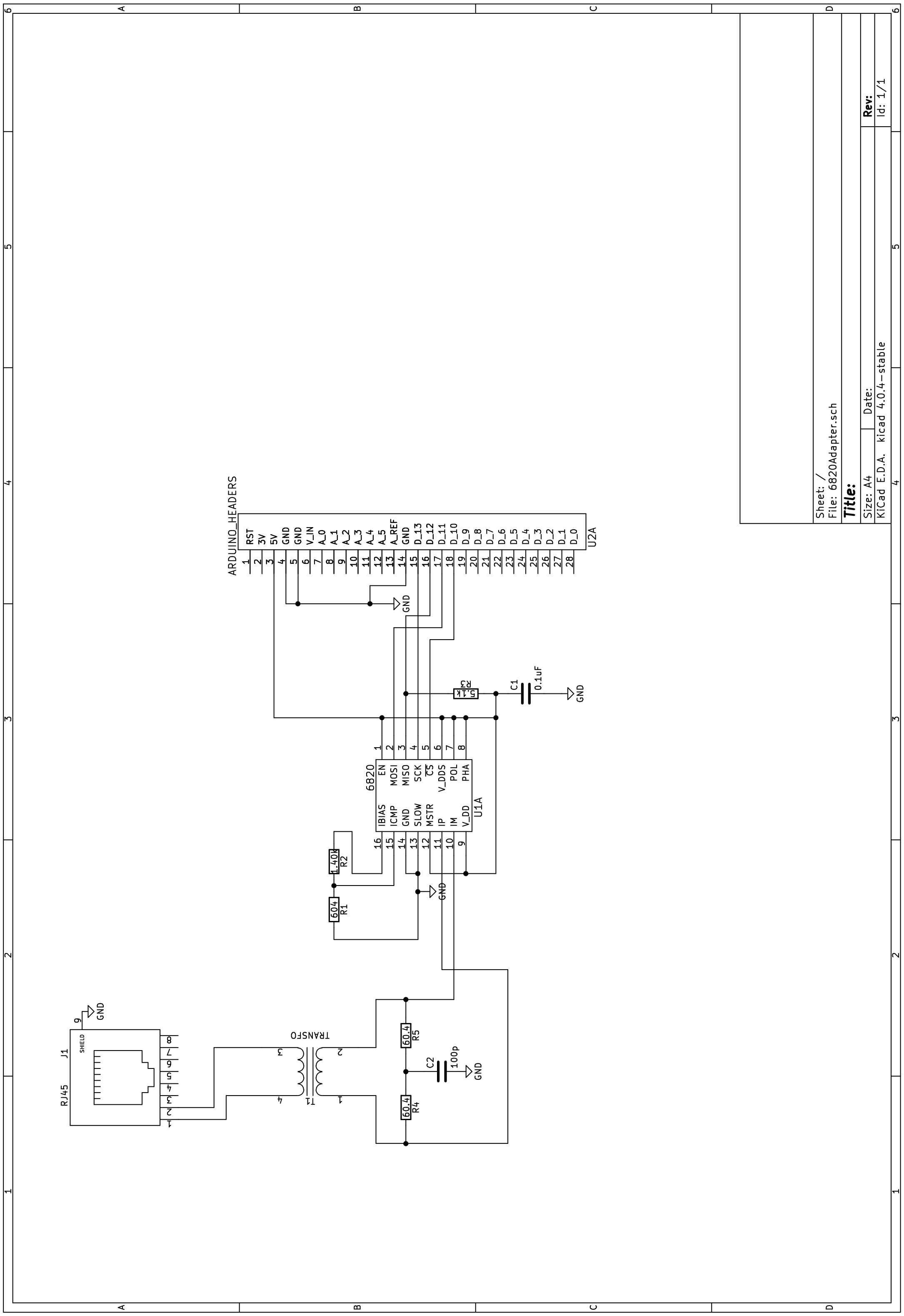

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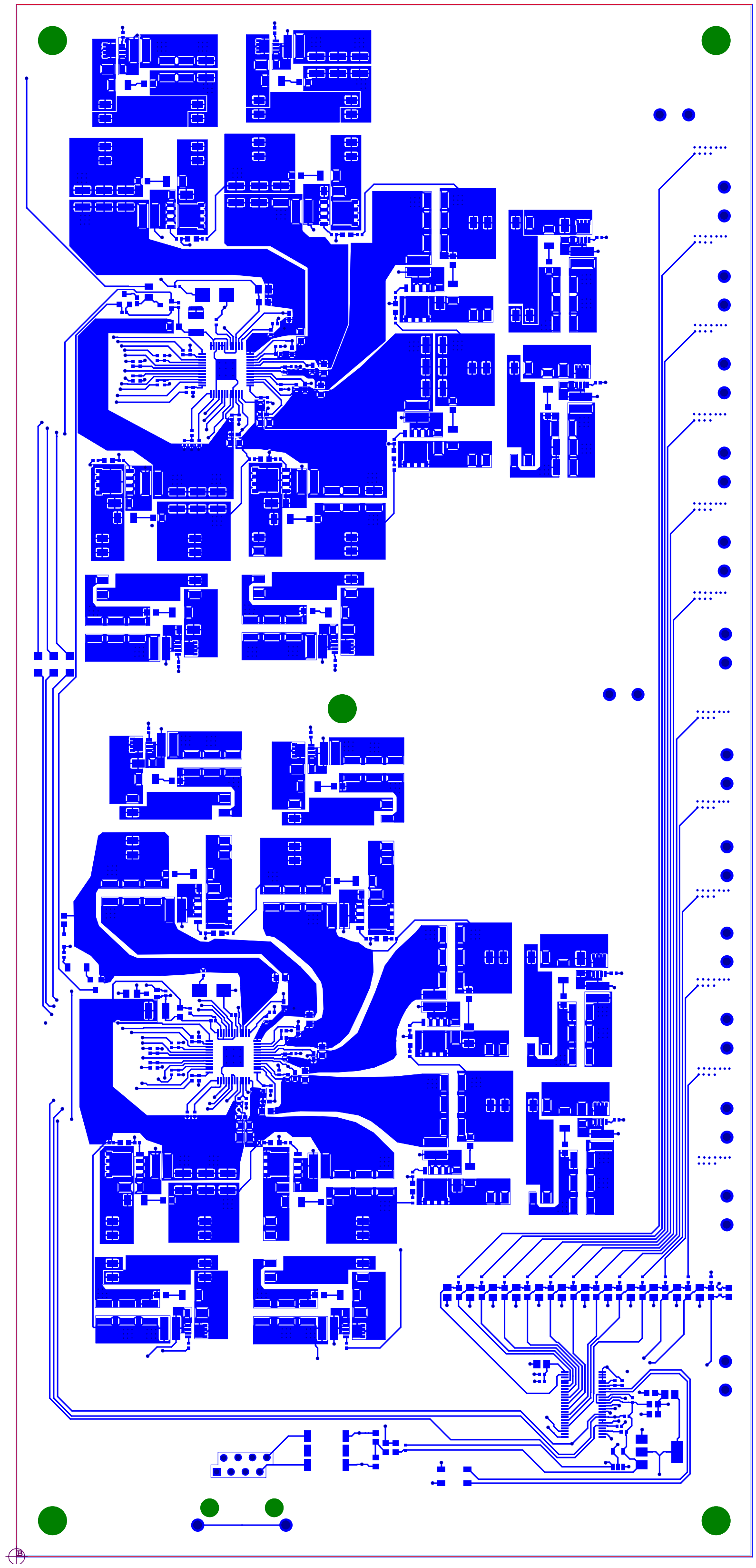

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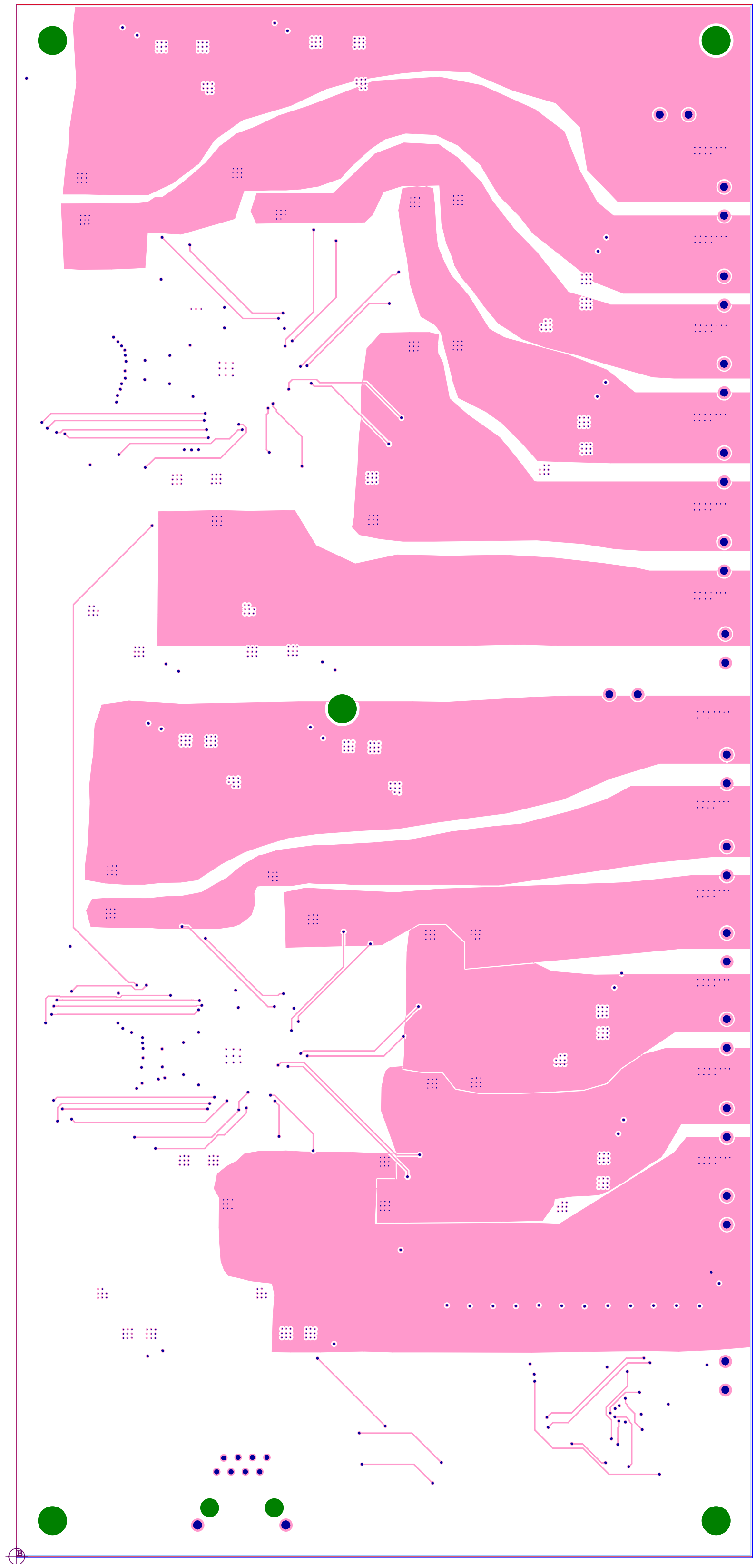

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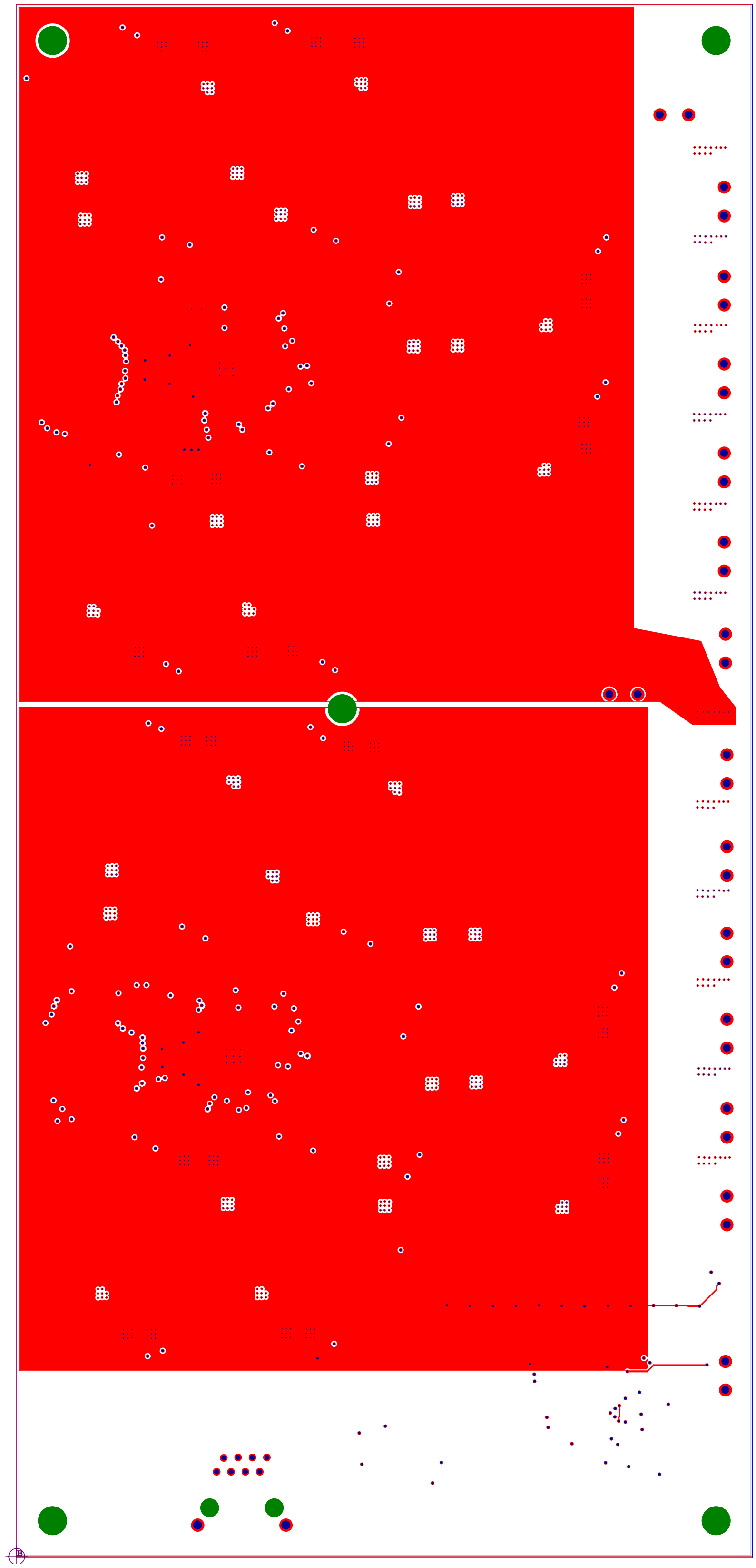

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