Active Cell Balancing for Solar Vehicle Battery Pack

ECE 445 - Project Proposal

Tara D'Souza, John Han, and Rohan Kamatar
Sponsor: Illini Solar Car
TA: Chaitanya Sindagi

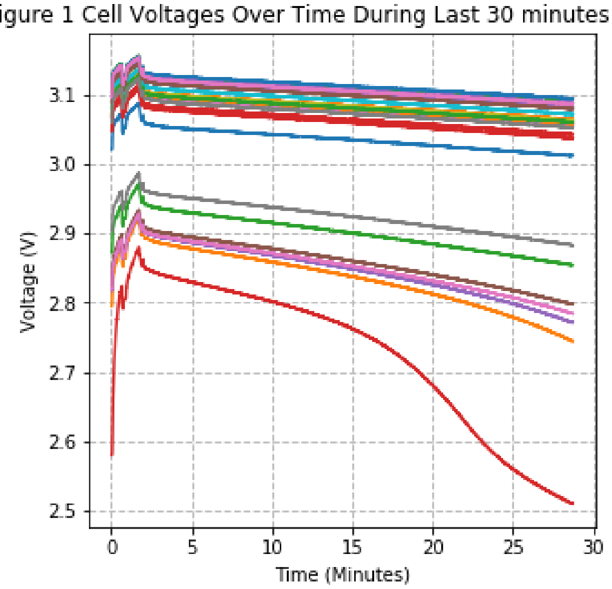
1. Introduction

1.1. Objective

In solar vehicles, charge is collected via a solar array and stored in a battery pack. Illini Solar Car (ISC) utilizes a lithium ion battery pack with 28 series modules of 15 parallel cells each. The nominal voltage of the battery pack is 100.8V and the maximum voltage is 117.6V. In order to ensure safe operation, each battery cell must remain in its safe voltage operating range (2.5 - 4.2 V). When any single module leaves the safe operating range, the entire pack must stop charging or discharging. During testing and competition, ISC has observed a steady unbalancing of the voltage of the 28 modules. As this occurs, the effective capacity of every module in the pack decreases to that of the weakest module. In previous competitions, this has rendered as much as 5% state of charge (SoC) unusable. Figure 1 shows how the imbalance in battery cells at the finish of the race resulted in shutoff of the car while some cells had a significant amount of charge remaining.

To combat this loss in SoC, we propose the addition of an active cell balancing system to ISC's battery pack design. Charge will be redistributed where it is needed. This will allow for the full capacity of each module in the pack to be utilized to power the car, rather than charge being dissipated through passive balancing or left unusable in the pack.

Figure 1 Cell Voltages Over Time During Last 30 minutes of Race



1.2. Background

Electrical vehicles represent a large portion of an emerging push for sustainable transportation solutions. As electric vehicle technology grows more reliable and efficient, it becomes increasingly more viable as an alternative to transportation powered by non-renewable energy sources. While ISC’s focuses remain largely on solar vehicle racing, advancements made in this sector display the viability of sustainable transportation which will soon make its way into commercial applications.

Solar Vehicle Racing is an engineering-based competition where university teams compete to design, build, and race the best car powered only by the sun. These competitions are 2000 mile endurance races that take place on public roads and highways over the course of many days. The primary goal is to build a reliable car that can maximize efficiency in order to travel the greatest distance during the event. An actively balanced battery pack will allow solar cars to travel further distances and/or faster speeds. In the context of competition, this will yield a more competitive solar vehicle. In a broader sense, this solution will increase the range, and thereby the viability of, electric vehicles as a form of sustainable transportation.

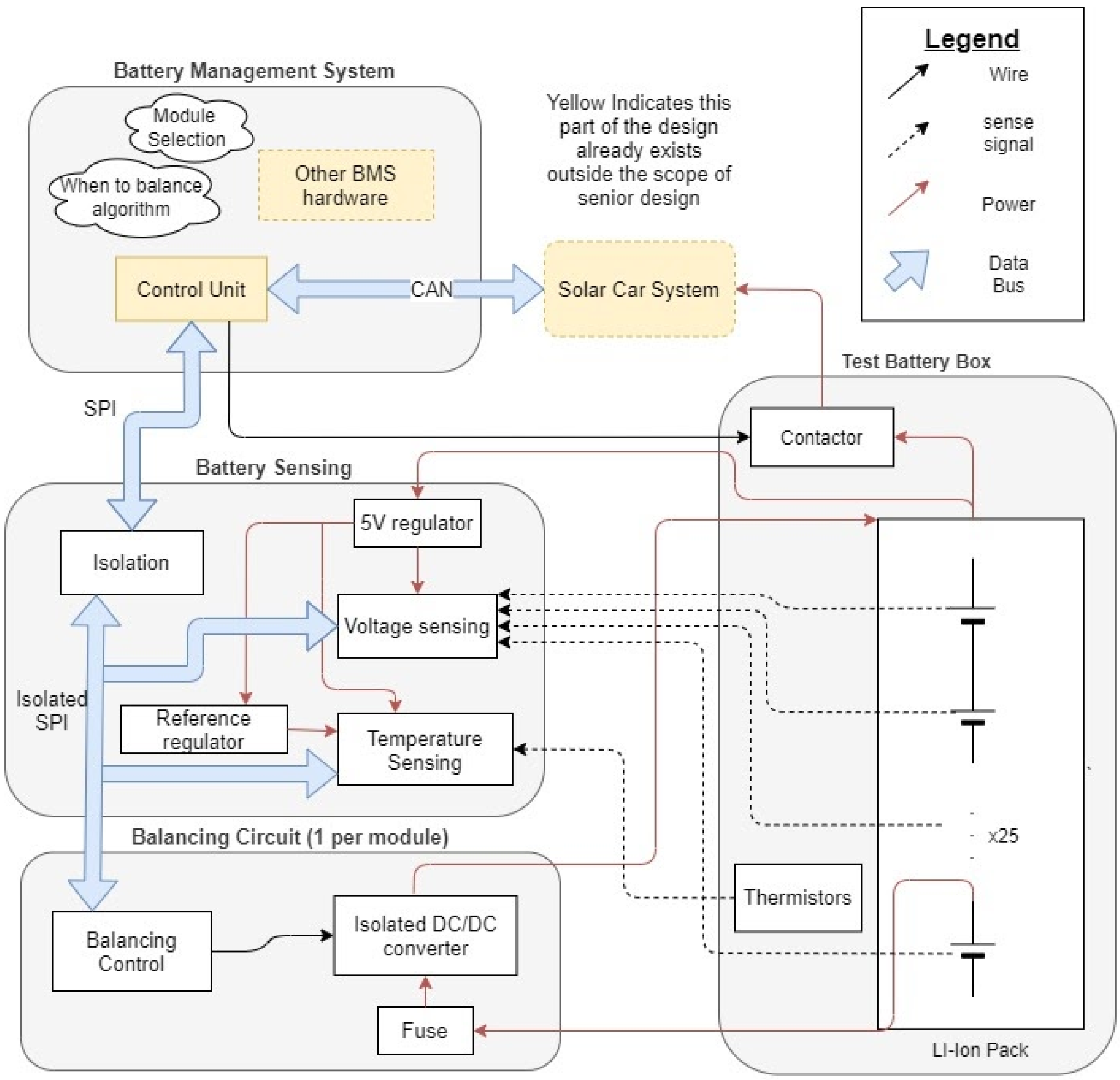
1.3. High-Level Requirements List

- Over the course of 4 hours, the active balancing system will be able to rectify at least 3% SoC through the redistribution of charge between modules.
- All battery cells must be monitored continuously and kept within safe operating conditions while balancing or powering the load. Batteries should be isolated in the case of a fault.
- The active balancing system should be efficient enough that no active cooling is required.

2. Design

Block Diagram

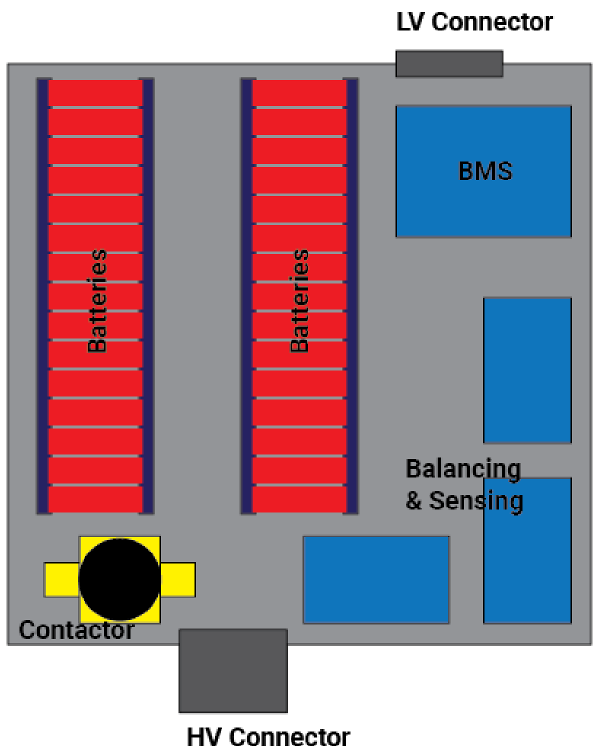
The design presented in the block diagram below uses a module that both senses and balances the batteries. The separate Battery Management System control software enables and disables balancing based on information from the voltage and temperature sensors and from commands from the rest of the car. The switching signals required for balancing come directly from the voltage sensor module based on measured voltage differences, thus the BMS control unit does not have to directly control each switch required for balancing.



Physical Design

The physical box will contain all the batteries and circuitry. The box will provide connections for high voltage power as well as low voltage communication and power. Inside the box the batteries will be grouped into two groups of 3P14S configurations. These groups will be connected in series. These cells along with the PCBs and contactor will all be screwed down to the base of the box. Figure 2 shows the general layout of components within the box.

Figure 2 Physical Layout



2.1. Battery Sensing

The purpose of the battery sensing block is to measure the voltage of each module and the temperature of the battery box. Voltage monitoring and temperature monitoring is essential for the battery management system to keep the battery pack in safe operating condition. Additionally, the control unit within the battery management system will use information from the battery sensors to make decisions about which cells to balance. The battery sensing module is a slave device on the SPI bus from the battery management system, and is connected via sense wires to the Lithium Ion battery pack.

2.1.1. Reference Voltage Regulator

The reference regulator provides a stable reference voltage, which is required to take temperature measurements across a thermistor.

Requirement: Provide a stable reference voltage ± 10mV at most

2.1.2. Voltage Sensing

The voltage sensing subsystem is responsible for measuring the voltage of each module and must do so at a high precision to aid in accurate decision making regarding safety and balancing. Current leakage for the voltage monitoring circuit should also be kept to a minimum. The voltage sensor should read each analog voltage using an ADC, and communicate those values to the BMS control unit as a SPI slave

Requirement: The voltage measurements from the voltage sensing system should be accurate to within 10mV as read on the BMS and compared to a direct measurement on a digital multimeter.

2.1.3. Temperature Sensing

The temperature sensor subsystem reads the analog voltage measurements from the thermistors and communicates them to the BMS control unit as a slave on the isolated SPI bus.

Requirement: Analog voltage output from thermistors must be converted into a temperature reading accurate to ±5°C as read from the BMS control unit and compared to an infrared thermometer directed at the same location within the test battery box.

2.1.4. 5V Voltage Regulator

The 5V regulator is required to bring power to the other components of the sening block. The module will take in input from the top of the stack and convert it to a PCB usable 5V.

Requirement: Output a regulated 5V ± 0.2V.

2.1.5. Isolation

The isolation subsystem provides galvanic isolation of the SPI bus between the Sensing and balancing modules and the master BMS control unit. This unit is necessary because the voltage monitoring unit should always remain connected to the battery pack even in the case where the rest of the car is isolated.

Requirement: This module must maintain galvanic isolation of >240V

2.2. Balancing Circuit

There will be one balancing circuit for each module in the battery pack, 28 in total. The function of the balancing circuit is to transfer excess charge from a module where balancing is enabled to the full pack. The balancing circuit for each module will take an enable signal via SPI and operate a DC/DC converter between a single module in and the full pack. The block interfaces as a slave on the SPI bus with the control unit of the battery management system and has power wires from the Lithium-Ion battery pack.

2.2.1. Balancing Control

The balancing control subsystem creates the high frequency switching signal necessary to operate a DC/DC converter. This system will be enabled based on the algorithm determined by the BMS control unit through an isolated SPI data bus.

Requirement 1: This module must be controlled by isolated SPI.

2.2.2. Isolated DC/DC Converter

The Isolated DC/DC converter will be in an isolated flyback topology, in order to boost the battery module voltage to the pack voltage.

Requirement 1: This module must have an low-side input voltage range of at least 2.5-4.2V and an output range of between 70-117.6V. Operation beyond said range is acceptable but will not be useful.
Requirement 2: This module should be capable of handling at least 2A of input current on the low-side.

2.2.3. Fuse

The fuse is a necessary requirement to ensure safety of the batteries in the case of a fault or short. The balancing circuit should operate slowly, at less than 50% of the module's total charge or discharge capabilities to avoid any thermal or safety problems, and the fuse should trip to stop rapid charging or discharging.

Requirement: Fuse limits currents in excess of 15A per module on the test pack

2.3. Battery Management System (BMS)

The function of the BMS is to keep the batteries operating in a safe condition by monitoring the battery sensors, the pack current draw and other inputs. The BMS is also the sole unit of communication between the battery pack and the rest of the car. The majority of the BMS system is outside the scope of the car; however, we will be writing additional firmware for the BMS to implement and test active balancing.

The BMS will include firmware that receives a command via CAN from the solar car system and enables active balancing if the other conditions for balancing are met. If the measured voltages necessitate balancing, the battery management control unit will also select which modules on which to enable balancing.

2.3.1. Module Selection Code

The module selection code determines which balancing circuit to enable. Enabling balancing transfers charge from a single module to the entire pack so heuristically balancing should be enabled on modules with greater than average SoC.

Requirement: Balancing is enabled only on 1 module at a time

2.3.2. When to Balance Code

This firmware will be programmed onto the BMS control unit. The purpose of this code is to properly determine when to enable balancing of modules based on current operating conditions and commands from the car.

Requirement 1: The BMS disables balancing in any situation where the pack would otherwise be isolated as outlined in the requirements for the BMS control unit.
Requirement 2: Balancing is enabled only by explicit command via CAN from another system on the car (balancing should not start by default without system knowledge).
Requirement 3: Regular messages on the CAN bus sent by the control unit confirm that balancing is still enabled.

2.3.3. BMS Control Unit (Out of Scope of Senior Design)

The control unit of the Battery Management System queries all peripheral hardware in the battery box to ensure that the batteries are operating within specifications outlined in the datasheet. This includes voltage, temperature, and current sensing. In the event that unsafe operation is detected, the control unit will isolate the batteries from the load and disable any balancing from occurring.

Requirement 1: While operating, all battery modules must remain within the voltage range of 2.5-4.2V.
Requirement 2: While operating, the temperature in the pack must be below 45°C while charging and below 65°C while discharging.
Requirement 3: While operating, the magnitude of the pack current shall not exceed 25A while charging and 65A while discharging.

2.4. Test Battery Box

The objective of the test battery box is to emulate the solar vehicle battery box in a way that can be used on a test-bench. The battery pack will consist of 3 parallel cells per module and 28 modules in series to form the pack. It will operate at the same nominal voltage as the full battery pack (100.8V) and have a max current output of 30A.

Each module will be sensed by the sensing and balancing block. The pack also provides power directly for the sensing and balancing block. The full pack provides power for the battery management system as well as the rest of the car in normal operation; however, the contactor is placed at the top of the pack and will isolate the batteries from everything but the sensing block in the case of an emergency or normal shutdown. This contactor is controlled by the Battery Management System.

2.4.1. Lithium Ion Pack

The battery pack houses 28 series modules of 3 lithium ion cells each, acting as a small scale module of the battery pack in use by ISC. Additionally, it will contain all peripheral hardware that makes up the battery protection system.

Requirement 1: All cells should be securely mounted such that vibrations or movement from any direction will not put excess stress upon the battery spot welds or cause the batteries to move from their mounting position.
Requirement 2: The materials chosen to construct the box and mount the batteries shall either be non-conductive or completely covered with kapton tape to prevent the possibility of any shorts.
Requirement 3: The voltage of each module shall be easily measurable and accessible for connections to battery balancing and sensing hardware.

2.4.2. Contactor

The contactor is the safety isolation mechanism in a solar car battery pack, during an emergency situation the contactor should be able to interrupt any current from the battery pack and fully isolate the battery from the rest of the car. Since this is a test pack that will not be subject to the same dangers as a full solar vehicle pack, only a single high-side contactor is necessary rather than a high and low-side contactor

Requirement: The contactor can interrupt connections of 240V and at least 60A, to be confirmed by the datasheet of the chosen component rather than bench testing.

2.4.3. Thermistors

Placed in various areas throughout the battery pack, the thermistors will be used to represent the pack temperature as an analog voltage. The placement and quantity of thermistors should be sufficient to give a general idea of pack temperature - a minimum of three thermistors is necessary to measure temperature in the front middle and back of the pack.

Requirement 1: The thermistors must have an operating range of at least 0-100°C.
Requirement 2: The resistance of the thermistors shall be accurate to ±1% at its respective temperature.

2.5. Risk Analysis

The isolated DCDC converter poses the greatest risk of completion of this project because it is required for any amount of cell balancing to be demonstrated. In order for active balancing to occur, energy must be moved from part of the battery to another. This converter is the circuitry that performs this transfer. This conversion is challenging because it will require moving energy from a 3.6V nominal cell to a 100.8V nominal pack. In addition to the significant voltage difference, both of these have large ranges over which the system must be able to operate. The battery cell will operate between 2.5V and 4.2V and the pack will operate between 80V and 117.6V. The system must have good performance near these limits as balancing will need to happen as the pack reaches maximum and minimum charge.

Additionally, this DCDC converter will contain the greatest power flow and therefore will require the greatest optimization in efficiency in order to meet the specified efficiency requirements.

3. Ethics and Safety

This project will deal with two significant dangers: high voltage and lithium-ion batteries. High voltage electronics pose a danger of electric shock. At higher voltages greater current can flow through the body, delivering more power and therefore an increased risk of injury and death [1]. We will minimize this risk by utilizing the one hand technique and always utilizing proper tools and safety equipment.

Lithium ion batteries pose a significant risk due to their high energy density and instability. In a 5 year period over 25,000 overheating and fire incidents involving lithium ion batteries were reported. However, this risk is only significant when the batteries are damaged or utilized outside of their specified operating conditions [2]. The safe operation of lithium-ion batteries is well defined by the American Solar Challenge regulations [3] under which ISC designs it's vehicles. These regulations require active protection of overvoltage, undervoltage, over current and over temperature where active protection means that the system will shut off automatically in any of the above fault conditions. The team will implement these systems and verify them before relying on them to provide protection.

While working with these dangers it is also important to minimize danger and risk to the public. The IEEE Code of Ethics states that it is our responsibility "to hold paramount the safety, health, and welfare of the public"[4]. We will ensure this through safe storage of our batteries, isolation of high voltage, and clear labeling of enclosures to protect the public from the dangers of our project. Our batteries will be stored in a fire cabinet while not in use and will always be stored at safe charge levels. Additionally, the battery pack will only be operated under supervision of our team members.

Should an accident occur during assembly or otherwise, the team will follow Division of Research Safety guidelines [5]. This includes always being prepared with proper safety equipment such as fire extinguishers and sand. The risk of thermal runaway of damaged batteries can also be mitigated through discharge in a saltwater solution. If a battery is damaged we will follow DRS procedures for disposal by placing the battery in a saltwater solution to discharge and contacting the DRS for proper disposal.

While high voltage batteries can be dangerous, with proper procedures and design, these risks can be mitigated which will allow us to create a safe and functional system.

4. References

[1] Division of Research Safety, "Electrical Safety In The Research Laboratory" *Division of Research Safety Library* [Online]. Available: https://drs.illinois.edu/Page/SafetyLibrary/ElectricalSafetyInTheResearchLaboratory [Accessed: Feb. 16th, 2021].

[2] Occupational Safety and Health Administration "Preventing Fire and/or Explosion Injury from Small and Wearable Lithium Battery Powered Devices" *Safety and Health Information Bulletins* [Online]. Available: https://www.osha.gov/dts/shib/shib011819.html [Accessed: Feb. 16th, 2021].

[3] Innovators Educational Foundation, *American Solar Challenge 2021 Regulations Release A* [Online]. Available: https://www.americansolarchallenge.org/ASC/wp-content/uploads/2020/10/ASC2021-Regs-EXTERNAL-RELEASE-A.pdf [Accessed: Feb 16th, 2021]

[4] Ieee.org, "IEEE Code of Ethics", IEEE Policies [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html [Accessed: Feb 16th, 2021].

[5] Division of Research Safety, "Battery Safety" *Division of Research Safety Library* [Online]. Available: https://drs.illinois.edu/Page/SafetyLibrary/BatterySafety [Accessed: Feb. 16th, 2021].