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EV, HEV, and Clean Energy Systems in the Undergraduate Curriculum: Cell Tester

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Executive Summary

This paper describes the development of a battery cell tester, its use in the Battery Workforce Challenge, and in the development of an undergraduate curriculum to address the future needs of the electric vehicle, hybrid-electric vehicle, and clean energy industries. A cell tester measures the charge/discharge, energy storage, temperature behavior, and possibly other characteristics of a battery cell under various conditions. The characteristics of a battery cell are needed for any application requiring the use of the cell. The presented cell tester was developed for cells intended for an automotive application. However, the tester can be used for cells in many other applications. The cell tester is a microprocessor-controlled linear constant current source capable of charging or discharging a battery cell up to a maximum current of 15 A using programmable charge and discharge profiles, and under various temperature conditions. The cell tester has been tested using several profiles including a constant-current-constant-voltage (CCCV), constant current discharge, Hybrid Pulse Power Characterization (HPPC), and vehicle drive cycles. The cell tester has a temperature controlled environmental chamber and a cell holder for testing the cell at high currents and various ambient temperatures.

Keywords: Education, Batteries, Modeling and Simulation, Measuring Methods & Equipment, Battery Management Systems.

1. Introduction

The Battery Workforce Challenge (BWC) [1], headline sponsored by the Department of Energy and Stellantis, and managed by Argonne National Lab, is a three-year competition in which student teams are challenged to design, build, and test a high voltage lithium-ion electric vehicle battery pack as a plug-andplay replacement for a 2024 Dodge Ram ProMaster E-Van. Twelve universities across North America were selected to participate and the competition started in September 2023.

Rose-Hulman Institute of Technology (RHIT) is a primarily undergraduate institution focused on engineering, science, and mathematics. Located in Terre Haute Indiana, it prides itself on its undergraduate focus (no PhD program, limited MS program) in an environment of individualized attention and support. RHIT has been ranked #1 in Undergraduate Science, Engineering, and Mathematics 26 years in a row.

One of the critical Year 1 deliverables for the BWC was a characterization of the provided 21700 Li-Ion cell. While most teams had either in-house cell testing capabilities or outsource options, RHIT decided to design and build their own cell tester. Building our own cell tester enabled our students to experience additional outcomes other than measuring cell performance. Those outcomes include designing a high current cell holder, designing a temperature-controlled cooling chamber, designing an electronic system with multiple failsafe systems, and writing software for CAN communication. While the cell characterization results were not as high quality as teams that used professional grade equipment, they were sufficient to complete the deliverables. After the competition, a second cell tester was developed and incorporated the lessons learned in developing the first version.

2. Cell Tester Version One

Undergraduate students from Rose-Hulman Institute of Technology developed the first version of the cell tester. The purpose of the circuit was to measure the capacity, resistance, and power capabilities of an INR21700 cell at various temperatures. Creating this test facility required the development of a temperature-controlled test chamber, a test stand to hold the cell and supply high currents with low contact resistance, and a control circuit to run the tests. The components are described below:

2.1. Overall Block Diagram

The cell tester used a Rigol DP932U DC power supply with voltage and current limits as the charging supply and a Rigol DL3021 electronic load for discharging the cell. At the current limit, the DC power supply acts as a constant current source, providing constant current bulk charging. At the voltage limit, the DC supply acts as a voltage source allowing constant voltage charging for the cell. The electronic load could be used for both constant current discharge and pulsed discharge current for an HPPC profile. Both of these devices were controlled by a system programmed by the students. A simplified block diagram of the system is shown below:

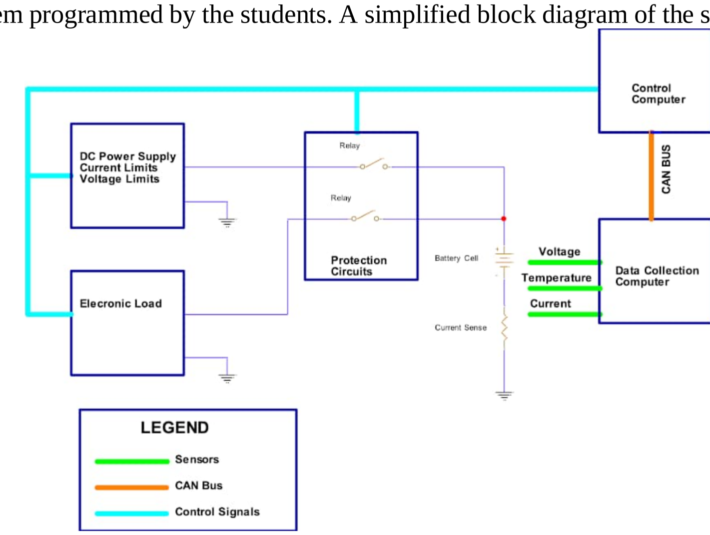

Figure 1: Block Diagram of the Original Cell Tester

2.2. Temperature Controlled Chamber

The testing chamber is a 7 ft^3 chest freezer filled with 300 pounds of sand, which increases the chamber's heat capacity and facilitates control of the chamber's temperature. The sand can be warmed by three 20W plant germination heating pads buried at two, four and six inches beneath the surface. Using a thermostatically controlled relay with freezer in conjunction with the pads, the temperature of the chamber could be adjusted with a testing range of 0° to 50° C. Upon reaching the desired testing temperature, the temperature was measured on the cell and at four locations around the chamber to verify that the chamber temperature remained stable. The stability of the chamber temperature increased significantly after the addition of the sand as ballast. A photograph of the test chamber is shown in Figure 2:

Figure 2: Cell Tester Temperature Control Chamber

2.3. **Test Stand to Hold the Cell**

To hold the cell during testing, a test stand was designed and built. It uses oxygen-free electronic OFE copper plates on either end of the cell, a bolt to tighten the connection, and lugs to connect to the circuit. A key feature is that the space under the cell is clear such that, should the battery experience a thermal event, it will fall onto the sand and the test operator can put additional sand over it. (The enclosed chamber can also be wheeled outdoors if needed.) Electrically, the cell holder provides a 4-wire measurement to accurately measure the cell voltage at the terminals of the cell. The picture below is the first iteration of the test stand made from fiberglass L-channels. The white wires shown are thermocouples for measuring the cell and chamber temperatures.

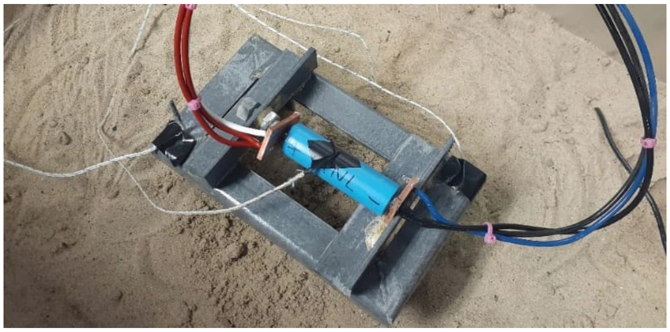

Figure 3: First iteration of the cell holding apparatus

2.4. **Circuit**

The cell tesing circuit consisted of a power multiplexor and over protection circuits. Electro-mechanical relays were used to connect the cell to the power supply for charging and to the electronic load for discharging. The protection circuit used windowed comparators that would trip if the current or voltage ranges extended beyond the recommended operating region of the cell as defined by the manufacture's datasheet. This analog protection was independent of and a backup to the software protection implemented in the testing procedure. Cell voltage was sensed by the comparators and compared to a reference. Current was sensed using a sense resistor and amplified before interfacing with the windowed comparators. The outputs of each comparator were wire-OR'd together and fed into a latch that would power down the relays and disconnect the cell if an over-fault was detected. The latch can only be reset by the operator pressing a physical switch. An emergency stop switch will also power down the relays, in the event that the operator wants to terminate the test and isolate the cell.

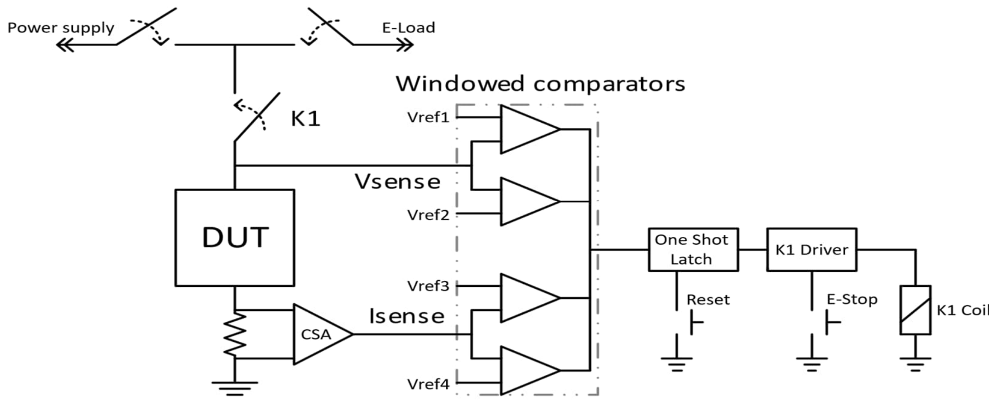

Figure 4: Circuit block diagram of the original cell tester.

2.5. **Software/Computer Control**

To keep in line with the goal of developing our students 'experience towards building a full battery pack, the computer control system was designed with abstractions that students would encounter when building that larger system. The students' previous coursework experience focused on a single microcontroller that interacts with sensors and actuators. To gain experience with a more complex system, the team decided to separate the control into two systems: a data collection computer (DDC) and a control computer (CC). The DCC was built using an Arduino Uno interfaced with various sensors and ADCs. The CC was a Raspberry Pi, which gave our students exposure to embedded Linux. The DDC took measurements and communicated them to the CC over CAN. Even though the bus has only two members, the DCC and CC, the choice of CAN allowed our students to get hands-on experience with CAN. Anecdotally, the students encountered troubleshooting issues with endianness and bus configuration, which deepened their understanding of how to integrate heterogenous systems. The CC software was developed in python and drove the instruments (DC load, power supply, etc…) via the PyVISA library, and the DCC was written in Arduino C. PyVISA allowed the students to gain experience implementing the various test protocols and low-level device interfaces in a language they were comfortable working in. Having the two controllers programmed in separate languages on different platforms provided valuable system integration experience.

2.6. **Lessons Learned**

Below, we briefly summarized lessons learned in the first version of the cell tester:

- *Solid-State Relay* - Back-to-back MOSFETs used as a solid-state relay could have served as a better solution to a mechanical relay. In the second version of the protection circuit, both MOSFETS and relays are used in series for added protection and multiple ways to isolate the battery cell.
- *Sand Ballast* – The sand ballast was necessary for stabilizing the chamber temperature. Although the heating power and cooling power were modest, the chamber temperature fluctuated by several degrees when either the heaters or the freezer compressor turned on. Initially, a small room heater was used to heat the chamber. Because the heater was too powerful, and the control system not fast enough, the temperature of the chamber was not controllable. To fix this, 300 pounds of sand was added to the chamber, and the high power heater was replaced by three 20 W plant germination heating pads.
- *Conflict Between Safety Systems* – Both hardwired analog and software-controlled limits were used in the system to guarantee safety. With the setup, conflicting safety limits can occur, and it is not always easy to find out which safety system caused the system to shut down. More diagnostics are needed in the system to determine the cause of a shutdown. Also, the limits should be tunable.
- *Limits Easily Exceeded Based on Battery Cell State of Charge* – For the pulsed test, it was noted that the cell voltage limits were easy to cross when the cell is close to the fully charged and fully discharged

cell operational limits. This required changes to the testing protocol to accommodate testing when the cell is close to these limits. This was an example to students of how a system changes based on the knowledge gained using that system.

- Students also learned that proper documentation is required for software development and circuit design. For a large system like this one, many conflicts occurred where software designers and circuit designers blamed each other for a problem that was not well documented on either side.

3. Cell Tester Version 2

Version one of the cell tester had the goal of exposing undergraduate students to developing, designing, and building a large complex system that includes analog, digital, thermal, mechanical, and software aspects. Taking lessons learned from the first cell tester system, the second version was created with the intent of developing a more maintainable and robust system that is higher power and more flexible. In addition, the updated version has the goal of demonstrating a mixed analog/digital system that demonstrates analog system design combined with microprocessor control, with three levels of safety: software limits, analog circuits with digital logic hardware, and manual protection consisting of an abort pushbutton and an emergency shutdown pushbutton. These levels of protection were incorporated in the first version of the cell tester. In the second version, the protection circuits and software were made more explicit and easily adjustable. The microcontroller is an Arduino Due programmed in Simulink, which allows students from various disciplines to work, understand, and manipulate the complete system, including the analog design.

The overall system is a computer controlled linear constant current source that can charge and discharge a single battery cell. A block diagram is shown in Figure 5:

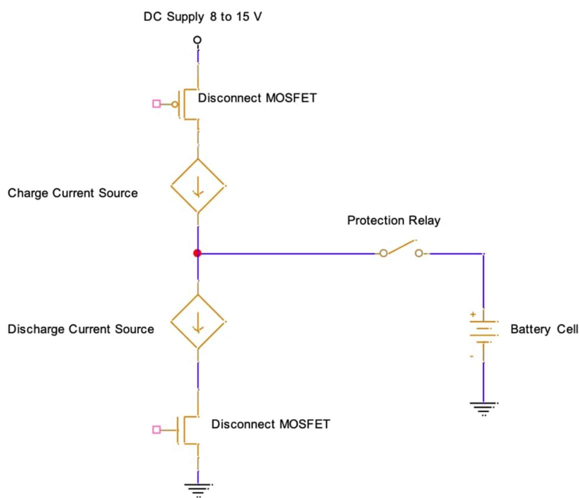

Figure 5: Block diagram of the updated cell tester.

The charge and discharge sources are linear current sources controlled by an Arduino Due. When charging, the charge current source can range from 0 and 15 A while the discharge current source is set to zero. During discharge, the discharge current source can range from 0 and 15 A while the charge current source is set to zero. The MOSFETS and relay are provided for circuit and battery cell protection. In case of a fault, the current sources are set to zero, the MOSFETs are turned off, and the relay is opened. This provides three levels of safety for electrically disconnecting the cell. When the current sources are set to zero, they provide a high impedance path to the cell, which is essentially an open circuit. When the MOSFETS are off, they also introduce a high impedance path to the cell. Finally, during a fault, the protection relay is opened which electrically isolates the cell.

As an example of the electronics used in the cell tester, the circuit for the charging current source is shown below. This figure shows the linear charging current source, the disconnection MOSFET, the protection relay, and the battery cell being charged:

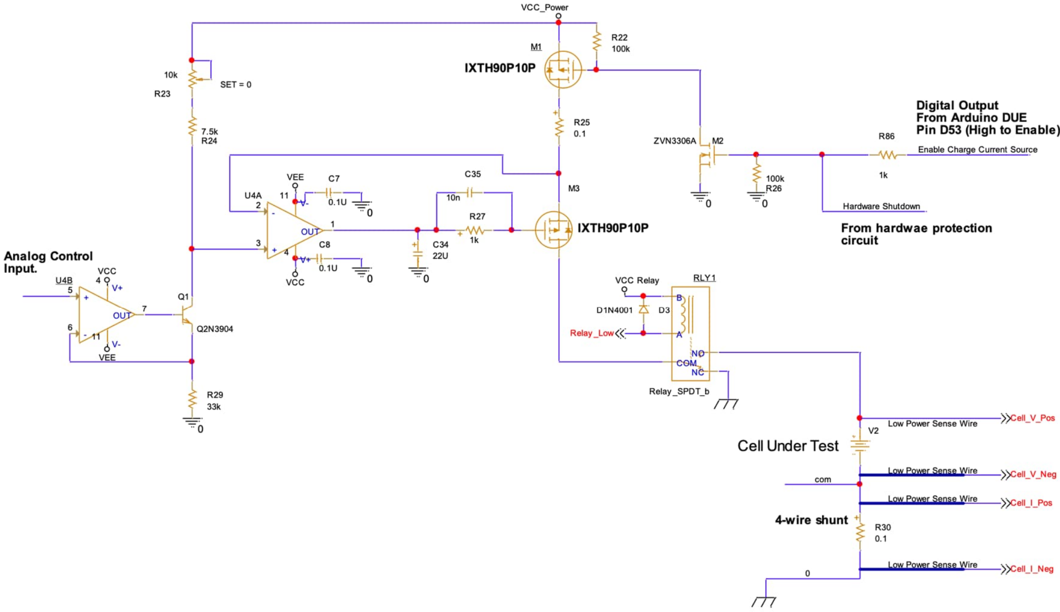

Figure 6: Linear current source used to charge the cell.

This is a linear current source controlled by an Arduino Due. Charging can be shut down by the Arduino through M1, M3, or the relay. In case the computer fails to shut down and disconnect the cell from charging, the analog protection circuit below will turn off M1 as well as open the relay:

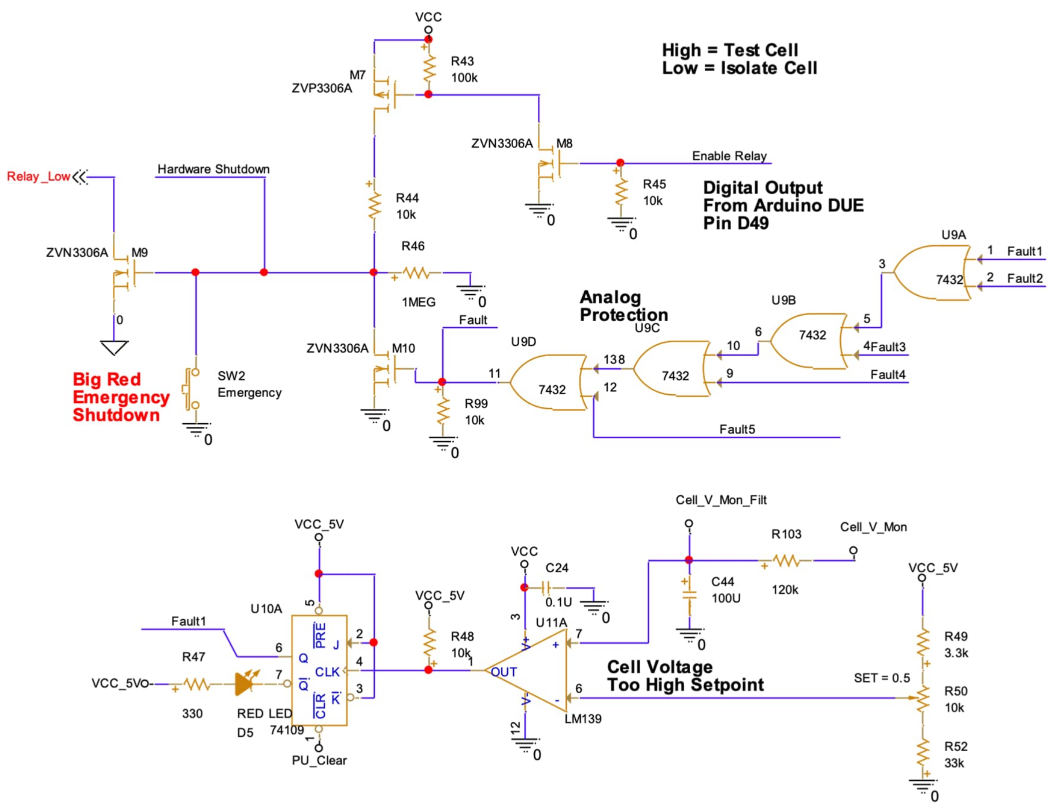

Figure 7: Analog safety limits for the cell tester

The hardware shutdown circuit is completely independent of the microcontroller and can function to isolate the battery cell based on five different faults. The specific fault shown in the circuit is for cell over voltage.

Note that the circuit uses discrete logic OR gates that will function even if the microcontroller fails. M1 and the relay will be opened in the case of manual shutdown, cell over voltage, or any of the other four faults detected by the circuit. This analog and manual protection is meant to be a failsafe backup to the control computer, which should shut down the charge or discharge process in the case of a fault **before** the hardware safety circuit detects a fault.

This level of integrated electronics, where there is redundant fault protection at different levels of the design, is typically not taught in undergraduate classes. Power electronics used in Electric Vehicles, Hybrid-Electric Vehicles, and clean energy systems require multiple levels of safety. One of the goals of this project is to expose students to the requirements of several levels of safety that are required in systems of this type, specifically software limits, backup hardware limits, and manual overrides.

4. Cell Tester Version 2 Measured Results

The cell tester can be programmed with just about any charge/discharge current profile as long as the current is between ±15 Amps. We have tested it with three different profiles: a constant constant-current-constant-voltage charge profile followed by a constant current discharge, an HPPC cycle, and a vehicle drive cycle. The cell tester has been tested with lithium 21700 cells. We can test these cycles at various ambient temperatures using the thermal chamber discussed above.

4.1. Charge/Discharge Cycling

Below are the results of the cell tester for a CCCV charge followed by a constant current discharge. The cycle is run three times to test the capacity of the cell. The tested cell is an LG 21700M50T:

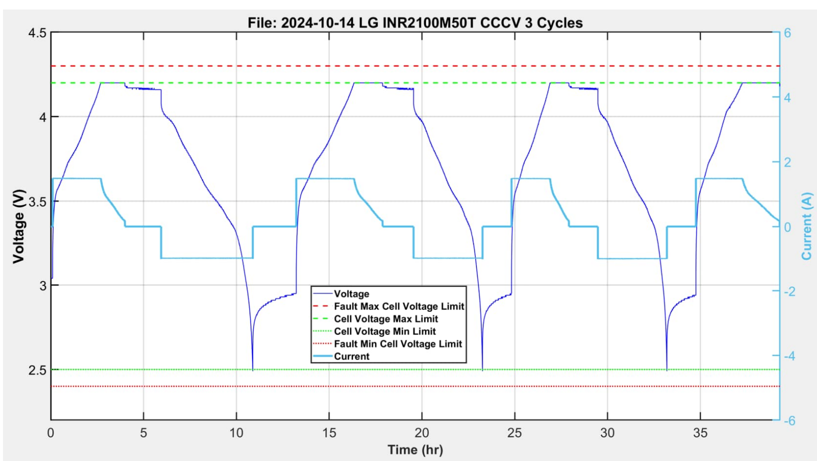

Figure 8: Results of three charge-discharge cycles for an LG INR21700M50T cell

This plot shows the cell current and cell voltage over three cycles. Positive current charges the cell and negative current discharges the cell. The LG 21700M50T is approximately a 5 Ah cell. The cell is charged at C/3 and the cell is discharged at 1 A. At the start of the cycle, the cell rests for a temperature soak for a specified time, 10 minutes in this case. After the soak, the cell is charged with a CCCV profile, with a maximum voltage limit of 4.2 V. The cell then rests for a specified time, two hours in this example. The cell is then discharged at a constant current of 1 A until the cell voltage hits the lower limit of 2.5 V. The cell again rests for a specified time, and then the cycle repeats.

The example above shows the operating limits of the cell of 2.5 V to 4.2 V. The charge profile uses the voltage limit of 4.2 V along with a minimum charge current in constant voltage mode to determine the end of a charge cycle. The voltage limit of 2.5 V is used to determine the end of a discharge cycle. Also shown are the software fault limits of 2.4 V and 4.3 V. If the voltage ever hits these software limits during a cycle, the cycle will be terminated, the relay will open, and the system will indicate a fault. These faults and this protection are microcontroller controlled. The analog hardware limits are slightly higher than 4.3 V and slightly lower than 2.4 V. These limits are not shown on the plot and should never be triggered unless the microcontroller fails. If the analog hardware limits are triggered, the system halts, the protection MOSFETs and relay are opened, and operator intervention is required to reset the system and start another run. Also note that there are hardware and software limits for cell current and cell temperature, which are not shown on the plot.

A second plot collected for the same run as shown above shows the Amp-hour capacity of the cell for three consecutive charge-discharge cycles:

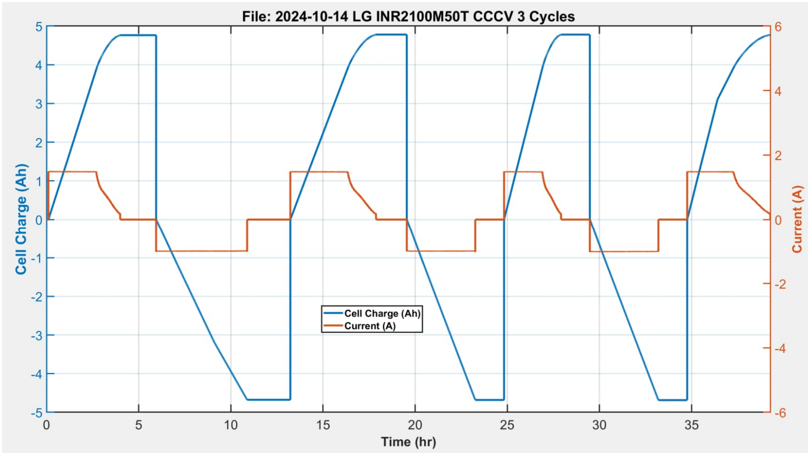

Figure 9: Results of three charge-discharge cycles for an LG INR21700M50T cell

The plot shows cell current and cell Amp-hours for an LG21700M50T cell. Positive current charges the cell and negative current discharges the cell. The results show that the capacity of the cell is about 4.68 Ah.

4.2. **HPPC Cycles**

The cell tester can be programmed with various cycles using MathWorks Simulink and Stateflow. Below is an example of an HPPC cycle performed on a 21700 cell. This profile is based off of the USABC Hybrid Pulsed Power Characterization (HPPC) [2] which was developed to characterize batteries for hybrid and electric vehicles. The USABC HPPC profile was adapted by the organizers of the Battery Workforce Challenge for educational purposes while also providing a testing profile suitable for cell characterization.

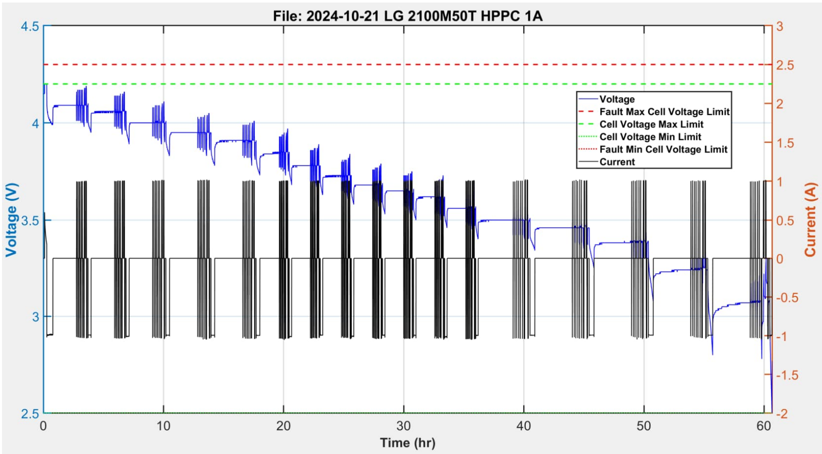

Figure 10: Results of an HPPC cycle for an LG INR21700M50T cell

Not shown in Figure 10 is that the cell goes through a temperature soak, is then charged with the cell manufacturer suggested CCCV charge profile and then rests for an hour. After this initial cell preparation, the cell is discharged with an HPPC profile. Shown on the plot are the cell voltage and cell current. Note that positive current charges the cell and negative current discharges the cell. At the start of the test, the cell is initially discharged down to 90% SOC to avoid issues of overvoltage in the HPPC profile that has high charge and discharge currents at various battery SOC's. In this test, an HPPC charge/discharge test is run, and then the cell is discharged with a constant current until the next SOC level where, after a short rest, the HPPC runs again. The test terminates when the battery is discharged and/or the HPPC discharge pulse causes the cell to reach its lower operating limit of 2.5 V. The plot shows the cell voltage limits of 4.2 and 2.5 V, and shows the software fault limit of 4.3 V. All of the software and hardware limits previously discussed are still in force for this profile.

A zoomed in version of the HPPC plot from Figure 10 is shown below:

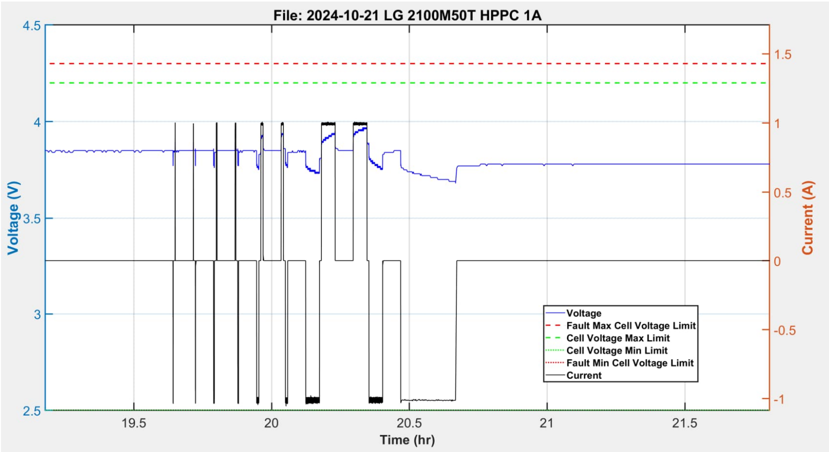

Figure 11: Zoomed-in results of an HPPC cycle for an LG INR21700M50T cell

A second plot of the same HPPC run is shown below:

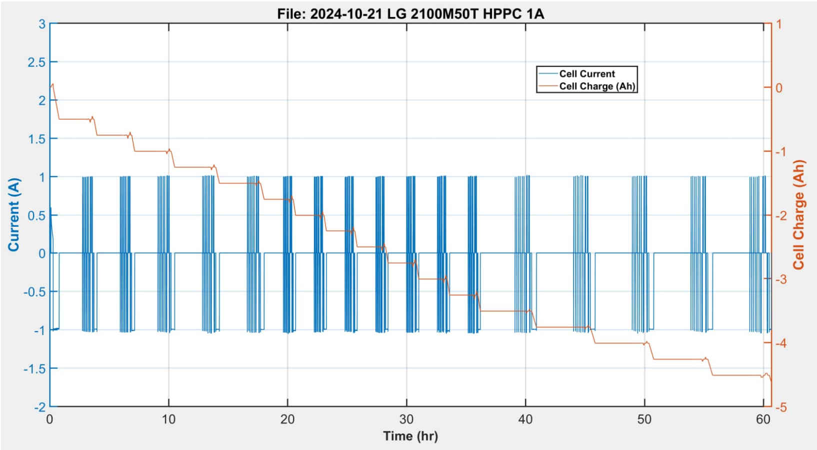

Figure 12: Results of an HPPC cycle for an LG INR21700M50T cell showing current and Ah removed.

Figure 12 shows the cell current, and the cell Amp-hours of charge removed. Note that the plot starts with zero Ah removed (100% SOC) and ends at about 5Ah (0%SOC).

4.3 Drive Cycle

The cell tester can be programmed with a vehicle drive cycle if the vehicle power versus time and the number of cells in the battery pack are known. If the power for the vehicle is known, the vehicle power can then be divided by the number of the cells in the vehicle battery pack to yield the cell power versus time for the drive cycle. The cell tester can then calculate the current in real time by dividing the cell power from the drive cycle by the real-time cell voltage. An example of a drive cycle is shown in Figure 13.

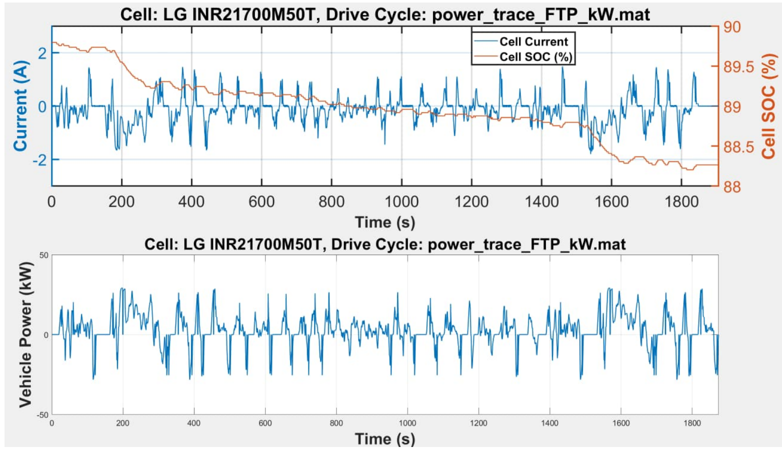

Figure 13: Results of a drive cycle for an LG INR21700M50T cell

The top plot of Figure 13 shows the cell current in Amps and the cell SOC in percent. The bottom trace is the vehicle power from the drive cycle. Note that when vehicle power (bottom plot) is positive, the vehicle is accelerating. Accordingly, when the vehicle is accelerating and the power is positive, the cell current is negative showing that the cell is being discharged. When the vehicle power is negative, the vehicle is regeneratively braking, and the cell current is positive, indicating that the cell is charging.

A zoom of the vehicle power and cell current is shown in the plot below. In this plot the current is multiplied by negative 1 (-1) to allow the vehicle power and current to be compared:

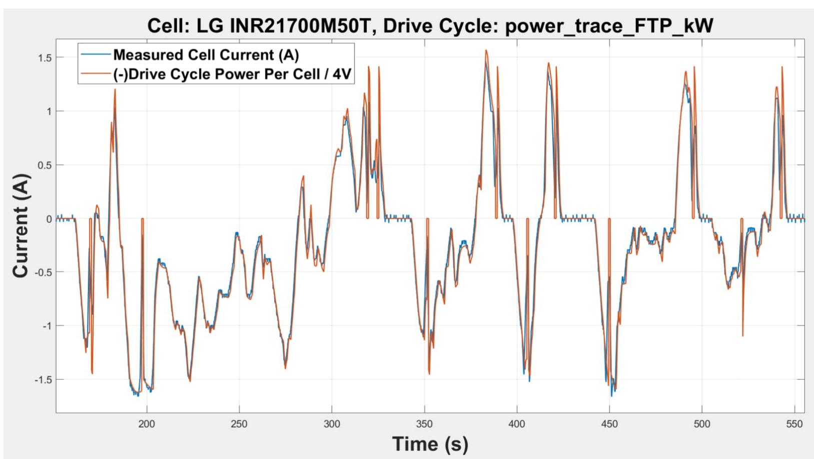

Figure 14: Results of a drive cycle for an LG INR21700M50T cell showing current tracking

The plot shows good fidelity between the requested vehicle power and cell current, indicating that the current source and control loop has high enough bandwidth and power to follow the drive cycle. A final plot shows the cell current and cell voltage during the drive cycle. The plot shows that the cell did not hit any voltage limits during the cycle indicating that the vehicle power did not have to be limited due to battery constraints:

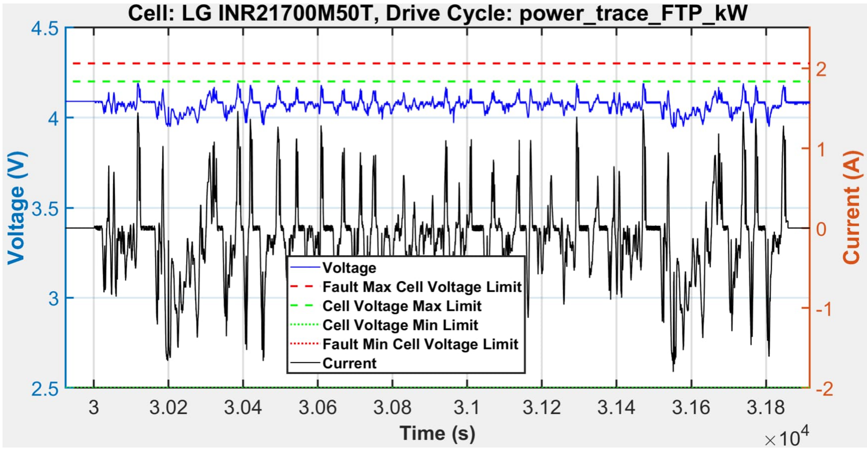

Figure 15: Results of a drive cycle for an LG INR21700M50T cell showing cell maximum voltage limit

5. RHIT EV/HEV/Clean Energy Curriculum Development

To address the upcoming need for engineers in the electric vehicle, hybrid vehicle, and clean energy sectors, Rose-Hulman is developing a minor concentration area to address the topics needed by engineers that will enter those fields. This is a multi-disciplinary area that includes mechanical engineering, electrical engineering, and chemistry. The existing courses intended for this minor are listed below: A new course in Clean Energy Circuits and Systems will be created.

- ME359 Vehicle System Modeling – Using Simulink, basic powertrain components are investigated for both an EV and an ICEV. Simple models of energy (electricity/fuel), motive (motor/engine), and transmission (none, multi-speed) are created with increasing levels of refinement. The course concludes with students creating a model of a vehicle of their choosing.
- ME559 xEV Analysis and Design – Using open-source data for an engine, motor, and battery, the simple component models of ME359 are improved. Various levels of hybridization are explored. The course concludes with blend strategies for a split parallel vehicle.
- ECE 454 System Level Analog Electronics - Analysis and design of Op-Amp circuits: wave shaping circuits, Schmitt triggers, power amplifiers, high power buffers, controlled current sources, peak detectors, sample and hold circuits. Precision Op-Amp Circuits. Non-ideal properties of Op-Amps.
- ECE 556 Power Electronics: DC Power Supplies - Analysis and design of AC-DC and DC-DC converters. Linear, basic switching, charge-pump, and fly-back topologies. Introduction to devices used in power switching supplies. Thermal management.
- CHEM 276 Battery Technology – An introduction to the chemistry of batteries featuring a lab where students build and test a ZnCu galvanic battery.

6. Future Work

With the capabilities of the version 2 cell tester, we intend to do the work listed below. The topics listed will be used to verify the operation of the cell tester and simulation model. In the process of completing this work, an eye will be kept on developing related courses in support of the EV/HEV Clean Energy Curriculum listed above.

- The cell tester will be used to measure the performance of an LG INR21700M50T cell using CCCV charge profiles, constant current discharge profiles, and USABC HPPC profiles at various ambient temperatures. The measured results will be compared to simulated results using a Gamma Technologies model derived from a chemical model of the cell.
- Lifetime studies of the LG INR21700M50T cell using repeated charge and discharge profiles.
- Development of a programmable charging system with passive cell balancing circuit, including redundant safety systems, real-time control using a microcontroller, and mixed analog and digital systems.

Acknowledgments

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2. *United States Advanced Battery Consortium Battery Test Manual For Electric Vehicles*, Revision 3.1, U.S. Department of Energy Vehicle Technologies Program, INL/EXT-15-34184, October 2020.

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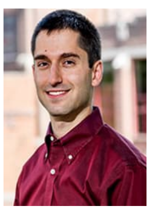

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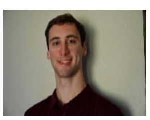

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