Energy Storage and Electric Motor Systems Projects for Hands-on Student Learning

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ABSTRACT

Advance Vehicle Technology Competitions (AVTCs) have been around for 30 years. Since 1994, the Hybrid Electric Vehicle Team (HEVT) at Virginia Tech has participated in AVTCs to pursue hybrid technologies. HEVT participated in a four-year AVTC called EcoCAR 3. At the beginning of the competition, HEVT introduced an ultra-rapid onboarding process, the Independent Study (IS) program, to involve non-seniors with the team. Although the IS program provides an incredible experience to non-seniors, it lacks hands-on experience related to the actual work students do once they become full-fledged team members. The challenge is to introduce two hands-on supplemental projects: the energy storage system (ESS) and the motor system. Each project is considered low voltage (LV) for safety and simplicity, however high voltage techniques are used for learning purposes. The LV ESS is used to power up an LV motor system. To limit depletion of the battery energy, another LV motor system is used as a generator to recharge the LV ESS. The lead faculty advisor, Dr. Douglas Nelson, and the project manager, Andres Coello, are working in congruence to introduce a smooth transition of the projects into HEVT's IS program. The hands-on projects are expected to last one semester. The goals are to guide students in the design, construction and testing of both systems. The hands-on supplemental projects are also meant to aid the Applied Automotive Engineering (AAE) curriculum by filling important knowledge gaps current AAE modules are missing.

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GENERAL AUDIENCE ABSTRACT

The Hybrid Electric Vehicle Team of Virginia Tech has participated in Advanced Vehicle Technology Competitions since its inception in 1994. These competitions challenge universities to reengineer and convert a vehicle into a hybrid vehicle. The goal is to train the next generation of automotive students by providing real world engineering experiences. The latest Advanced Vehicle Technology Competition is a four-year competition called EcoCAR 3. Due to complexity of the project, the Hybrid Electric Vehicle Team introduced an onboarding process to recruit and teach students the required knowledge of hybrid vehicles. To further improve the program, two projects are created to provide hands-on experience and visual learning about the electric layout of a hybrid vehicle. The first project is a low voltage battery pack and the second project is a low voltage motor dynamometer system. Both projects complement each other, meaning the battery pack acts as a power supply to the motor system. Overall, these projects are chosen to provide a good understanding to incoming students in the onboarding process about batteries and motors. Finally, practices used by the Hybrid Electric Vehicle Team are implemented in the project designs to improve the overall experience of students in the onboarding process and to improve knowledge transfer.

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1 Chapter – Introduction

The Hybrid Electric Vehicle Team (HEVT) at Virginia Tech is a senior design project that competes in Advance Vehicle Technology Competitions (AVTCs). The main goal of AVTC competitions is to train the next generation of automotive engineers. It has been 24 years since HEVT's inception and the team has redesigned and re-engineered several vehicles into hybrids electric vehicles. Currently, the team completed the final year of the current four-year AVTC called EcoCAR 3.

Given that the project is considered a senior design project, the majority of the team members previously were seniors. To reduce the turnover rate, the team implemented an ultra-rapid onboarding process to involve non-seniors with the team several semesters before their senior year. This process was recently implemented during EcoCAR 3 Year 1. Although the onboarding process is valuable to improve students' knowledge about hybrids, it lacks hands-on supplemental material related to the actual work students do on the vehicle. Therefore, the main goal of this thesis is to create a curriculum of two hands-on supplemental projects to aid the onboarding process for new students joining the team. The projects consist of the design and testing of a low voltage (LV) Energy Storage System (ESS) and an LV motor system dynamometer. In addition, the two hands-on supplemental projects are being developed to contribute to the Applied Automotive Engineering (AAE) curriculum.

The AAE project is a collection of educational content for students without prior automotive knowledge to help students overcome the steep learning curve in AVTCs. Automotive competitions such as AVTC have a span of several years to complete the project. Students that join the project midway need a way to get up to speed. For that reason, the AAE curriculum was created to help students learn critical knowledge to help students contribute on their own teams. The knowledge provided is not usually learned in academic classes.

1.1 Motivation for New Curriculum Development

Students that join HEVT are introduced to the onboarding process for one semester to learn the skills to become an effective team member. During this semester phase, students are taught necessary software skills and perform small weekly assignments relatable to their chosen subteam. Major shortcomings of the current onboarding process include the lack of hands-on work, non-cross functional team projects and lack of real-world applications that relate to the vehicle. For that reason, new hands-on projects are explored to improve the overall experience of the onboarding process.

During the creation of the curriculum, several engineering aspects are considered. Since the team concentrates on the hybridization of conventional vehicles, creating a project of the electric layout of hybrid vehicles on a scale model provides several beneficial traits to students. Students gain knowledge regarding power distribution, energy resources, mechanical and electrical design, and safety procedures. Therefore, the curriculum chosen is two hands-on supplemental projects that can work and be tested independently or together. These projects are an LV ESS and an LV motor dynamometer system. It is identified as low voltage because the electrical system is under 60 volts [1]. This is a chosen design consideration to reduce complexity and ensure both systems are not high voltage, which require special connectors and design considerations for safety.

Since HEVT deals with high voltage systems during the hybridization of a vehicle, high voltage practices are used in the curriculum development to improve the students' learning. This way, students are able to obtain knowledge on electric layouts of hybrid vehicles by filling educational gaps in the onboarding process before joining the team.

1.2 Research Objectives of New Curriculum

The objective of HEVT is to train the engineers of tomorrow. Therefore, this thesis provides a curriculum development to improve the onboarding process of HEVT. The curriculum is separated into two hands-on projects that provide knowledge of batteries and motor systems. Below are the main research objectives:

1. Introduce hands-on repeatable projects for the onboarding process of HEVT that relate directly to the work done in hybrid vehicles.
2. Educate students about electric vehicle components such as batteries and motors.
3. Explain electrical system design, voltage/current, series/parallel cells, cell connections, insulation, wire and fuse sizing.
4. Explain control interface, torque and speed command of motor systems.
5. Introduce thermal systems to dissipate losses.
6. Develop and document mechanical and structural design of LV ESS and motor system.
7. Analyze the thermal mass temperature rise data from both LV ESS and motor system.
8. Develop documentation to reuse systems for future iterations.
9. Develop assignments to go with hands-on projects.
10. Provide recommendations based on lessons learned.

1.3 Thesis Organization

The organization of the thesis begins by first introducing the reader to background information of the onboarding process and how the project manager role relates to the curriculum development. A literature review section is explained about benefits of improving the onboarding process of an organization. Furthermore, literature contains information on battery systems, battery cells, battery management systems (BMS), motor systems, contactor logic and how these components are important for both safety and education on hybrid vehicles. Next, detailed information about the LV ESS project is further explained with components and design considerations chosen. Additionally, the LV motor dynamometer system design is described in detail. Operations of both systems are explained within their own sections. Lastly, results and analysis of both projects are explained with recommendations to improve the current setup.

2 Chapter – Project Management

AVTCs have been around for 30 years to provide a training ground for future automotive engineers. Each year, competitions grow in both complexity and scope, and project management techniques are valuable to ensure success and meet project goals [2]. For this reason, AVTCs created a new leadership position, the project manager, for all participating universities during the previous AVTC EcoCAR 2.

Since the inception of the project management position, HEVT has implemented planning, risk analysis, cost analysis, cost management, human resources and stakeholder communication techniques. Although these processes are non-technical tasks, technical knowledge of the project is required to understand the impact of delayed tasks and create recovery plans to conform to the schedule. Therefore, HEVT prefers the project manager to be a graduate student with a Bachelor's of Science in Mechanical Engineering to have the knowledge required prior to learning project management techniques.

During the creation of PM processes at the beginning of EcoCAR 3, HEVT implemented an ultra-rapid onboarding process to reduce the turnover rate of students. As important as the onboarding process is, it currently does not provide hands-on supplemental projects that relate directly to the work students do once they join HEVT. The project manager leads the onboarding process. As a result, project management plays a huge role in the implementation of the hands-on supplement projects to ensure students are accommodated in separate subteams, the transition is smooth from the previous process to the new onboarding process, and assignments are documented to reuse the projects in the future

2.1 HEVT Onboarding Process

In addition to being an EcoCAR 3 team, HEVT is also considered a senior design team at Virginia Tech. To be considered a senior design team, HEVT requires about 25 mechanical engineering (ME) undergraduate students to join the team during their senior year. For this purpose, HEVT created an onboarding program called the Independent Study (IS) program. Students are now required to join the IS program to eventually join HEVT as a senior.

The independent study program is essentially a class where students learn about the competition and the team. The main goal of the independent study program is to prepare students to be functional team members before they join the team during their senior year. Students are encouraged to join the program during their junior year to learn what is required of team members and be prepared for their senior year. This gives a great advantage to HEVT since it provides a smoother transition from graduating to new senior team members.

HEVT is preparing junior students to join the team once they are in their senior year to meet staffing requirements. Every semester, approximately 15 IS students are recruited. This means that by the next year, tentatively 30 students can join the team. It is important to recruit additional students given that some students decide not to return to the team. However, there has been an approximate 100% retention rate of IS students due to the quality of the project. Although HEVT needs to recruit ME students, computer engineer (CpE) students are recruited during every fall semester for the advance driver assistance systems (ADAS) subteam. In addition, electrical engineer (ECE) students are actively recruited to provide help to the ECE subteam. To visualize the recruitment process, a flowchart is shown in Figure 2-1.

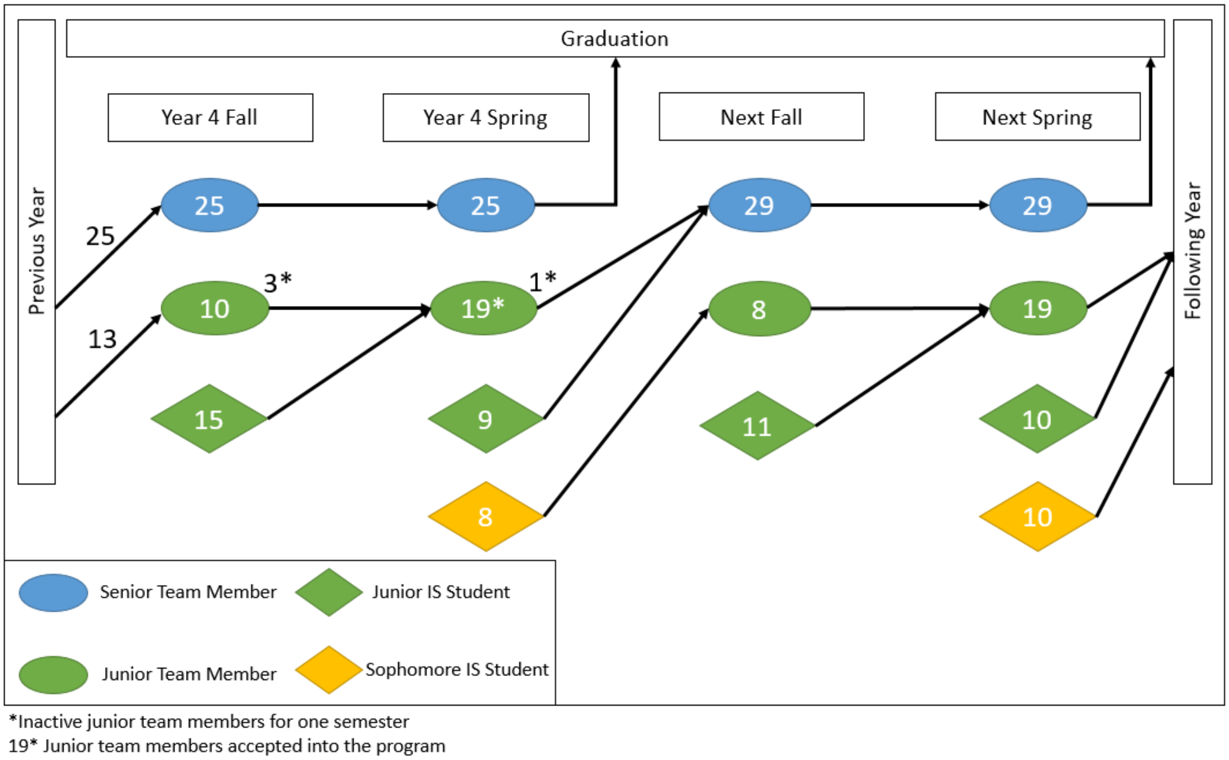

Figure 2-1: 2017-2018 Student progression path with independent study program strategy (adapted from Dvorkin, et al., "Strategies to Improve Performance at a High-Turnover Engineering Organization", *ProjMAN International Conference of Project Management*, 2015), used under Fair Use, 2018 [2]

Figure 2-1 shows the ME and ECE student progression path in HEVT. ADAS students are not included because the hands-on supplement does not directly affect members on the ADAS subteam. By the time Year 4 started, all seniors went through the IS program before joining HEVT. In addition, 13 sophomore IS students joined as junior team members. In the spring of Year 4, some students were not asked to come back to the team for two reasons: to reduce the load of graduate students and to improve the output quality of work in the team. Starting next year, the team will be staffed with 29 seniors, 8 junior team members, and 11 Junior IS students. As seen in Figure 2-1, HEVT is expected to meet staffing needs next year.

Understanding the requirements for students to join the IS program is important. Depending on the major, HEVT is able to provide credits that could count towards graduation requirements. Since the hands-on projects only affect ME and ECE students, only those majors are discussed in the next subsection.

2.1.1 Mechanical Engineer Majors Credit Requirement

Given HEVT is a senior design project, the ME department provides credits to team members because of ME 4015/4016. Prior to senior year, students are able to receive a maximum of six credits for IS towards graduation requirement. For this reason, it is crucial to begin recruiting ME students at the end of their sophomore year. Once students reach senior year, members are able to count another six credits for the senior design class. Therefore, HEVT is able to offer a total amount of 12 credits that count towards graduation requirement for ME majors.

2.1.2 Electrical Engineer and Computer Engineer Majors Credit Requirement

Working with the ECE department has been a bit more difficult but HEVT has been able to secure credits for EE or CpE students interested in the project. Prior to senior year, students are able to receive a maximum of three credits for IS towards graduation requirement. For this reason, it is ideal to recruit EE and CpE students during the fall semester. Once students reach senior year, members are able to count another six credits for the senior design class. Therefore, HEVT is able to offer a total amount of nine credits that count towards graduation requirements for EE and CpE majors.

2.2 Current Onboarding Program Findings

The IS program strategy is advantageous for many reasons. This program ensures senior team members have at least one semester of experience prior to joining the senior design project and the program reduces the turnover rate. Prior the IS program, the team often had IS students without a structured program. This is the first time HEVT has implemented a structured onboarding process since 1994.

Previously, most team members except graduate students would only be involved in HEVT for two semesters. This reduced the team's productivity by spending the first few months to onboard new students. Therefore, the turnover rate is a key metric that needed change. Up to this point, the IS program has reduced the turnover rate to 38%. This is a complete success given the previous turnover rate used to be approximately 85%.

By the end of Year 4, 56% of students were non-seniors. This is an incredible turn of events given that the team used to be senior-dominant. By involving students in an earlier academic year, students are able to leverage their skills and increase the knowledge transfer between students. Figure 2-2 provides the academic year of team members in EcoCAR 3 Year 4.

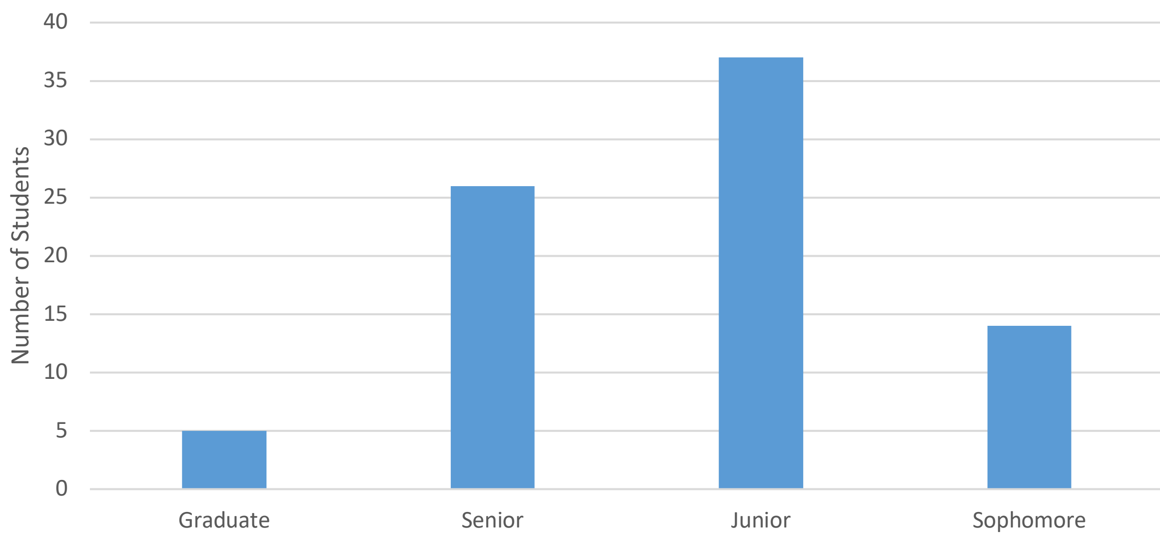

Figure 2-2: 2017-2018 academic year breakdown of current team members

Finally, the retention rate of the IS program is approximately 100%. There are students that do not come back the next semester due to Co-Op, internships or class conflicts. When class conflicts fully prevent students from participating in the project, the leadership team does not invite them back.

Even though the IS program has been a success, there is room for improvement. Graduate students are responsible of teaching incoming students the material of the IS program. Therefore, it is important to incorporate repeatable projects on each subteam to decrease the load for graduate students. The controls and mechanical subteams have developed a decent repeatable projects but electrical and ADAS subteam require improvements. To improve the onboarding process, incorporating a new and repeatable curriculum is needed, where the main three cross-functional subteams (mechanical, controls and electrical) work together. The two hands-on supplemental projects will encourage students to learn educational gaps from the AAE curriculum for AVTCs and will provide a more hands-on aspect which is lacking in the current onboarding process. The hands-on projects overview is discussed next and Chapters 4-5 covers them in detail.

2.3 Project Overview and Timeline

As previously explained, the hands-on supplement projects consist of the design and testing of an LV ESS and an LV motor system. Students are required to use the LV ESS to power up an LV motor. To limit depletion of the battery energy, another LV motor system is used as a generator to recharge the LV ESS. The second motor also acts as a load for the first motor, forming a simple motor dynamometer. The generator is be connected to the LV ESS to keep the battery cells from quickly depleting. The goal for the motor system project is to create a motor dynamometer. In addition, the hands-on supplemental projects goal is to improve the IS program by creating repeatable projects that relate directly to the work students do once they join HEVT as a team member. An overview of the overall system is shown in Figure 2-3.

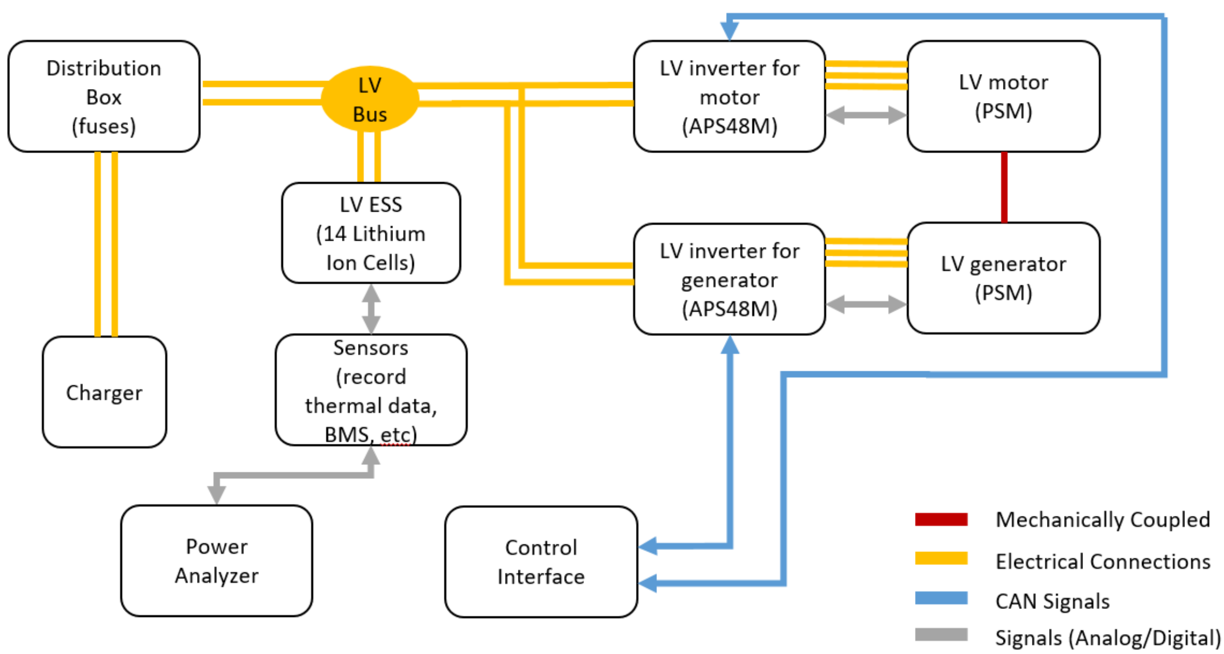

Figure 2-3: System diagram of the hands-on supplement projects.

The main components of the overall systems are the charger, the LV ESS and both LV motor systems. Both LV motor systems are connected to a control interface (supervisory controller) via Controller Area Network (CAN). The control interface is used to oversee all communication within the motor components. Likewise, the control interface monitors current or voltage during operation, commands torque, commands current, and monitors motor temperatures. A power analyzer is used to monitor battery voltage, current and power out of the battery terminals. All battery charging is required to be attended to ensure safe shut-down of all systems. To protect battery charging, a battery management system (BMS) is in place to protect the battery cells and ensure charge balancing.

The hands-on supplemental projects challenge incoming students to design, build and test the electric powertrain of a hybrid in a small scale. To complete the projects, incoming students are separated into the three main subteams: mechanical, electrical and controls. Note that subteam does not mean degree major. An ME student can be on the electrical subteam. Each subteam has responsibilities to complete the project which can be seen in Table 2-1.

Table 2-1: Subteam responsibilities for hands-on supplement projects

Subteam	Responsibilities
Mechanical	Mounting motor and inverter Housing for battery cells and support of LV ESS Develop component layout of LV ESS Dynamometer setup (Torque generator) Generator needs to be in place to recharge the LV ESS Needs to sustain torque from LV motor Thermal considerations for all components
Electrical	Size and fuse design of LV ESS system Present schematic of LV ESS Indicate all components required for safety Manual Service Disconnect (MSD) Work with mechanical to route electrical connections in CAD Physical wiring/system diagrams (compared to electrical schematics)
Controls	Model battery & motor Present schematic of LV motor system Develop control requirements Bench test LV motor system Interface between LV motor and LV ESS system Contactor control logic, battery management system Use of supervisory controller (laptop or component) Document charging requirements and procedures

Before starting the hands-on supplement projects, new IS students are required to complete general training to become familiarized with the software and hybrid vehicles in general. Once the general training is complete, the projects start and follow the project management life cycle. The project management life cycle has four phases: initiation, planning, execution and closure [3]. Given that the projects are somewhat complex; the life cycle of the hands-on supplemental projects is one full semester.

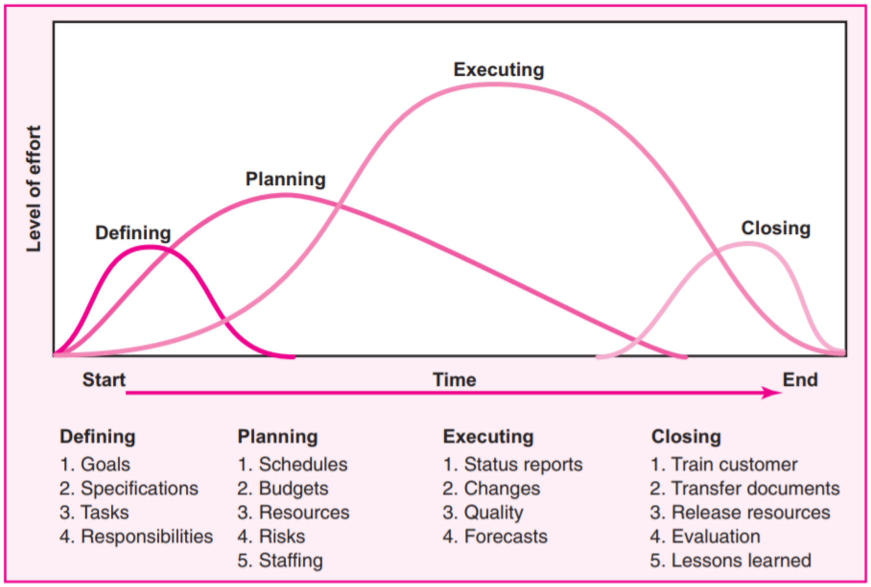

Figure 2-4. Project life cycle stages of the hands-on supplement projects (From Larson, et al., Project Management: The Managerial Process 5th Edition, 2010: 7-8), used under Fair Use, 2018 [3]

The defining phase consists of the selection of students to complete the project as well as the training required for students to be ready to move to the next phase. The planning phase consist of the concept design and concept selection of the project. Once students select a design and receive feedback from the lead faculty advisor, students start by designing the projects, procuring materials and document to prepare for the execution phase. Design reviews are also included in the planning phase to challenge and prepare students. The goal is for students to have a plan before building the project and be as prepared as possible for potential issues that could delay the project. The defining and planning phases are reduced on scope since the major components are already procured and guidance is given to the students to build the LV ESS system and LV motor dynamometer system. To build the projects, IS students follow the created designs. The components need to be bench tested. These tasks correspond to the execution phase. Finally, the closing phase of the product life cycle corresponds to testing, documentation, and lessons learned for the next students to start the project. In addition, a disassembly procedure should be in place to safely disconnect the LV ESS system and LV motor to be reused in the next iteration of the hands-on supplement projects.

2.4 Project Design and Selection

For students to fully create the project, first they must brainstorm to come up with different designs. Once the designs are created, a decision matrix is used to come up with the best design possible. These processes are referred to as concept generation and concept selection.

2.4.1 Concept Generation

The concept generation consists of a series of steps to come up with different concepts for the project. For this particular case, the new IS students are taught about three methods: Mind maps, 6-3-5 method and morphological charts [4]. These methods are taught to sophomore students during engineering design and economy class and reviewed again during senior design class at Virginia Tech. Mind maps is a method to generate concepts for a project. Students start with the problem and later on branch out to different solutions. The 6-3-5 method corresponds to 6 team members, 3 concepts each and 5 rotations around the table. The goal is for students to generate as many concepts as possible and after a full rotation, there is a discussion regarding the concepts. The third method taught is the morphological charts. This method deconstructs the problem creating different sub-functions. Later, solutions are given for each sub-function and concepts are generated by combining solutions for each of the sub-functions.

2.4.2 Concept Selection

After the creation of different concepts, determining the best possible outcome is next. The concept selection goal is to develop the best concept possible to meet the project goal.

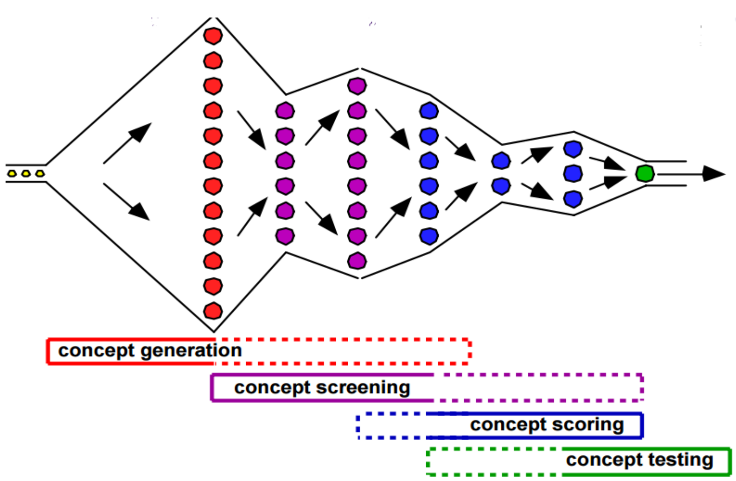

Figure 2-5: Concept development funnel
(From Ulrich, et al., Product Design and Development, 3rd Edition, 2004), used under Fair Use, 2018 [5]

Figure 2-5 shows a graphical representation to develop the best concept. There are two main stages in concept selection: concept screening and concept scoring. Concept screening is the process to reduce different concepts and provide further refinement and analysis. Concept scoring consists of the use of objective methods to reach an agreement of the final concept selection.

A chart or matrix is needed to objectively score different concepts. For simplicity and ease of analysis, the pairwise comparison chart is chosen. The pairwise comparison chart is also taught during senior design project class at Virginia Tech. First, the selection criteria are determined and these relate to key customer needs.

Table 2-2. Concept selection criteria

Selection Criteria	Description
Safety	Meet specifications standards, fuse & wire sizing, charging & discharging, vibration isolation (dampers)
Serviceability	Accessibility of components, assemble and disassemble procedure
User interface	Controls for user to interface with the components, Manual Service Disconnect (MSD)
Controller interface	Controllers used to interface with LV motor and LV ESS
Reliability	Quality of components and maintenance schedule
Manufacturing	Time required to manufacture parts
Component test structure	Accessible to move setup to different structures if required. Portable structure
Cost	Initial cost, maintenance cost
Noise/Vibration	Noise heard from the setup, vibration on mounts to be manufactured
Lightweight	Mass of cables, mounts, brackets and other parts associates with the project setup
Aesthetic Appeal	Consumer review of aesthetics, easy to handle and labels

After the creation of the selection criteria, the lead faculty advisor and the project manager determine a normalized weight for each selection criteria for the supplement project to be as detailed as possible. The pairwise comparison chart is then created and can be seen in Appendix B: Pairwise Comparison Chart template. The goal of the pairwise comparison chart is to compare a concept generation against the others. The selection criteria are then rated as “0” for worse than, “1/2” as equal to and “1” as better than [5]. The final step of concept selection is to rank the concepts and determine if solutions can be combined to improve the concept.

3 Chapter – Literature Review

To apply the hands-on supplemental projects into the onboarding process, research is done regarding the background knowledge needed to build an LV ESS and an LV motor system dynamometer. In addition, industry strategies are researched to ensure a smooth transition of HEVT knowledge transfer to incoming students. Likewise, aspects of project performance are researched as well. This chapter discuss the findings of different scholarly articles about knowledge transfer, battery cells and motor systems.

3.1 Onboarding Management Process

HEVT's onboarding process goal is to provide students the resources to learn relatable information about hybrid vehicles and engineering before fully joining the team. Currently, the onboarding process provides training to incoming students but it is lacking hands-on materials to better prepare students. Several tactics are furthered explored to find ways to improve the current onboarding process.

3.1.1 Towards Effective Knowledge Transfer

Power et al., in *Towards effective knowledge transfer in high-tech project environments: Preliminary development of key determinants*, argue to better promote knowledge transfer to improve project success [6]. Project success is important to ensure an organization secures future funding and provides the best education possible to employers. To provide the best experience possible, organizational culture plays an important role.

Power et al., suggests a conceptual model with five factors that are important to improve organizational culture and knowledge transfer: trust, rewards, communication, leadership and motivation [6]. Management of these factors are imperative given these could also be an obstacle in sharing knowledge. Trust provides a path for employees to work together and ease the transfer of knowledge [7]. Consequently, competence enables co-workers to build up trust [8]. Rewards are an incentive to motivate employees to perform specific tasks. Soft rewards are when incentives relate to team recognition. Studies found soft rewards are the most important to transfer knowledge [9]. Communication is an enabler for knowledge transfer. Face to face communication has been found to be more effective than using social networking technologies [10]. Leadership on a project is a main driver for direct knowledge transfer. Specifically, participatory leadership style reduces employee fear and enables communication across different hierarchy levels in an organization

[11]. Motivation is important to ensure project success. For projects where motivation plays a large role, intrinsic motivation provides a positive influence in knowledge transfer because project tasks are found to be interesting [11] [12].

Understanding these five factors are important in incorporating repeatable projects and improving the onboarding process. As previously mentioned, competence is an enabler for trust among co-workers. The LV ESS and LV motor system projects will enable students to gain trust among coworkers. Graduate students, responsible in teaching the projects, ensure face to face communication and participate in the project to further improve communication. Students should be required to document and disassemble the projects as part of their assignments to receive a sense of soft rewards. Finally, both hands-on supplements act as visual learning for students to improve their motivation and to ensure knowledge is transferred to improve the success of the project.

3.1.2 Effects of Knowledge Characteristics on Organizational Effort

Kang et al, in *Revisiting knowledge transfer: Effects of knowledge characteristics on organizational effort for knowledge transfer*, identifies three characteristics that affect the effectiveness of knowledge transfer: tacitness, difficulty, and importance of knowledge. As time progresses, organizations have to create new knowledge to maintain their success. This knowledge creation is a process of combining and organizing existing information to pass down to the organization for future success [13].

Tacit knowledge is referred to the knowledge that is difficult to transfer using notes or verbal communication. In this article, it has been found that tacit knowledge has a negative effect on knowledge transfer [13] [14]. Although the option of reducing the tacit knowledge could increase the performance of knowledge transfer, tacit knowledge can be learned and transferred through practical projects and visual learning. Frequent meetings between knowledge sources and students are required in transferring tacit knowledge [15]. Lamb et al., suggests tacit knowledge can be learned through practical projects with relevant context of the organization [16]. In addition, Carlile et al. found that a common technical language is required to improve knowledge transfer. With the development of technical language, interactions between knowledge sources and students is most likely to increase [13].

The difficulty of knowledge is a factor that affects the transfer of knowledge. When knowledge is explicit, it could still be complex and difficult to understand for students. By increasing the knowledge difficulty, the knowledge transfer effectiveness is decreased and requires knowledge sources to interact with students more frequently [17]. Organizations should transfer important knowledge strategically for efficient knowledge transfer under limited resources [13]. This way, organizations are able to reinforce the specific knowledge and improve the knowledge transfer effort for the benefit of the organization.

These three knowledge transfer characteristics heavily apply to HEVT's onboarding process to improve the students' experience in the program. Given HEVT is a senior design project that competes in a four-year competition, it can be determined that tacit knowledge is transferred to incoming students. Therefore, implementing hands-on approach projects relatable to HEVT and hybrid vehicles will ease the learning process. Due to limited resources, strategically transferring knowledge is necessary for HEVT's graduate students manage the onboarding process effectively.

3.1.3 Senior Project Design Success and Quality: A Systems Engineering Approach

Flores et al., in *Senior Project Design Success and Quality: A Systems Engineering Approach*, discusses how soft skills encourage project design success. Soft skills are identified as communication, teamwork, and leadership. Lack of these skills, lack of high level view of the project, and lack of work on a team environment are culprits that hinder project success [18].

Project success is based upon hard work, knowledge and determination of each team member. Communication skills are emphasized to develop end-to-end systems thinking. It is encouraged for an organization to require students to give weekly presentations on the status of the project. Students are able to practice and improve their communication and leadership skills [18]. Teamwork is an important factor in distributing responsibilities amongst a team. According to the United Nations Educational Scientific and Cultural Organization (UNESCO), it suggests that students benefit more from a project based instruction because students face challenges earlier on in their careers [19]. The International Council of Systems Engineering (INCOSE) encourage organizations to educate professionals to adapt to changes and challenges associated with the increasing complexity of systems [20]. Leadership skills allow students to work on a specific subsystem and encourage students to become subject matter experts on a particular component. This method ensures peer mentoring occurs and knowledge is strengthened [18].

Prior literature provides strategies to ensure knowledge transfer and project success. By implementing project based instruction on the onboarding process of HEVT, students are able to improve their experience in solving and facing challenges. Likewise, communications and leadership skills are developed across the program where teamwork is required to complete project goals. The onboarding process can be determined as a scaled senior design project where students learn to be better prepared when they join the team for senior design project.

3.2 Lithium Ion Batteries

Lithium ion batteries are used as an energy storage system (ESS) for EVs and HEVs. Due to their high specific energy and energy density, lithium ion batteries have led the EV market compared to other cell chemistries [21]. Lithium ion batteries are composed of battery cells connected in series, parallel or in series/parallel to form an ESS. Series connection increases the battery voltage and parallel connection increases the capacity or the amp-hour (Ah) of the battery. Different configurations are used depending of the needs of the application.

There are various types of lithium ion batteries, but normally these come in cylindrical, coin and prismatic shapes. Prismatic cells are normally used in the automotive industry but cylindrical cells are starting to gain popularity as a choice in the automotive industry [22]. Although there are several lithium ion chemistries and types, the general purpose of this thesis is not to analyze each of them, but to learn about the lithium ion battery behavior and safety precautions when building an ESS. As incoming students joining the team need to tackle the LV ESS hands-on supplement, safety is a great concern when dealing with batteries.

3.2.1 Personal Protective Equipment

The handling of battery cells must be treated with strict precaution to reduce the chance of an electric shock. According to Pretruzella et al. in his book of *Electric Motors and Control Systems*, "…the severity of an electric shock is the amount of electric current that passes through the body" [23]. The use of personal protective equipment during the handling and testing of equipment is paramount for safety. Specifically for equipment above 50 V, it is considered dangerous [24]. If equipment is alive, it is recommended to just use one hand to reduce passing current through the body. High voltage systems have the ability to force current through the skin, which is why special equipment is necessary when dealing with these systems [23].

Before handling battery cells, all personal protective equipment must be rated for the battery voltage rating. Several examples of electrical equipment include but are not limited to: rubber protective equipment (gloves), blankets, safety glasses, and tools (pliers, hammer, and screwdrivers). Rubber gloves prevent hands from coming into contact with energized systems. Blankets are used as an insulation between the energy system and the surface. Normally, blankets are used during the building and repair of battery systems. Safety glasses are required for every type of mechanical or electrical work and need to be compliant by the American National Standards Institute (ANSI). Tools such as pliers, hammers, and screwdrivers are needed for the installation of compressive plates or other overhead materials to build an ESS [23] [24].

3.2.2 Lockout and Tagout

Electrical lockout corresponds to the procedure of disabling the energy source of electrical power. A lock is used to disable the power from being turned on. Tagout is the procedure of placing a tag on the source to indicate the component mustn't be activated until tag is removed and service is complete. Generally, lockout and tagout are used as safety precautions during servicing electric equipment. Ensuring the system is not energized with a voltmeter is recommended to confirm that the system is not "live" [23].

During the voltmeter measurements in an un-energized battery system, voltage readings may appear between positive and negative leads. This phenomenon is called "ghost voltage". According to a support fluke document, *Ghost voltages – phantom readings can lead to the wrong diagnosis*, digital multimeter (DMM) may give false readings due to high input impedance coming from the DMM [25]. When an open circuit provides voltage readings using a DMM, the circuit is completed by the DMM and "…the capacitance between the hot conductor and the floating conductor forms a voltage divider in conjunction with the DMM input impedance" [25]. Low input impedance DMMs can dissipate the ghost voltage and determines if the circuit is not live.

3.2.3 Manual Service Disconnect

ESS above 60 V peak is considered high voltage (HV) in the automotive industry. As an HV system, complexity increases and several components are added to ensure the system is safe. The Manual Service Disconnect (MSD) is one particular component used during servicing to split the voltage of the battery pack in half. Hence, the ESS is not fully energized. The MSD must be in an accessible location and by removing the MSD from the ESS, it provides a shut-off for the HV system. The MSD acts as an energy source disabler, thus it must follow the lockout and tagout procedure. The MSD may also have a built-in fuse to protect the ESS in a faulty event [24].

The LV ESS hands-on supplement is lower than 60 V peak, which technically does not require an MSD. However, this concept and procedure is important for students to learn during the onboarding process.

3.2.4 Battery Charge/Discharge and Internal Resistance Behavior

In HEVs and EVs, batteries are used as the main electric energy source. Depending on the driver behavior of electric vehicles, batteries experience charge and discharge conditions. When batteries are discharged, the capacity starts to fade and the power is reduced, known as performance degradation. When cell internal impedance increases, battery power is reduced which also reduces the operating voltage [21] [26]. Several studies have found that lithium ion batteries age after cycling them several times [21] [26] [27]. Takei et al., present results that the capacity is reduced as maximum voltage is increased [27].

Lithium ion batteries specifications are nominal voltage, maximum allowable voltage, minimum allowable voltage and capacity (Ah). Although there are other specifications depending on battery type, these are the most important to understand the behavior. When a lithium ion battery reaches high or low voltage, current is limited by both the charger and the internal resistance.

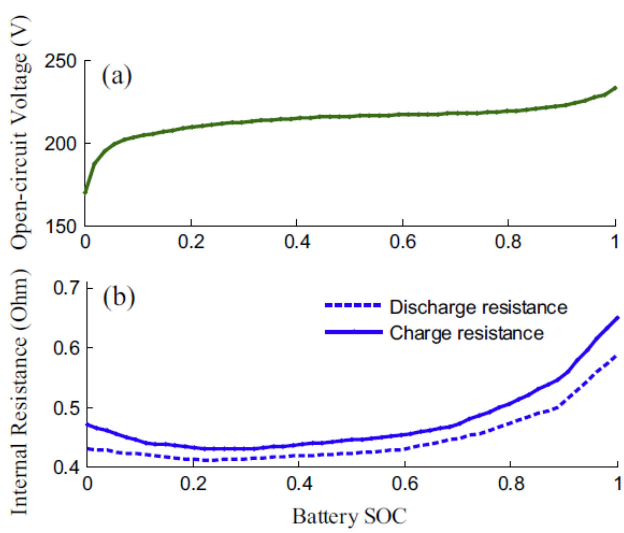

Figure 3-1: (a) Battery pack open circuit voltage and (b) discharge/charge internal resistance (From Yang, et al., Comparison of power-split and parallel hybrid powertrain architectures with a single electric machine: Dynamic programming approach, *Applied Energy*, 168, 2016: pages 683-690, used under Fair Use, 2018 [28]

Internal resistance increases and changes over battery operation and lifetime due to degradation [29]. Although high discharge rates occur when loading lithium ion batteries, these can self-discharge during storage. Normally, batteries in storage deplete due to high or very low temperatures which is explained more in the next subsection.

3.2.5 Thermal Management

Self-discharge of lithium ion batteries is not as important when used in EVs or HEVs, but it can be important when used in other types of applications when batteries are stored for long periods of time [21]. Linden et al., presented self-discharging data of a Sanyo C/LiCoO2 cells stored in temperatures between 0°C to 60°C. There is low self-discharge on ambient temperatures from 0°C to 25°C, however significant discharge occurs at temperatures stored at 60°C [30] [21]. Reports show a capacity retention of 75%, 89%, and 93% after storing cells at 60°C, 25°C, and 0°C for six months. Johnson and White et al., present results where cells sustain greater than 97% of capacity when cells are stored at 25°C for one month [31] [21].

As noted by Bandhauer et al., battery performance characteristics are sensitive to temperatures above 50°C and high state-of-charge (SOC) [21]. Lithium ion batteries used in automotive applications should be held below 50°C. As lithium ion batteries charge or discharge, the temperature of the cells start to increase. Depending of the pack design, interior cells may heat up faster than others and propagate heat across the pack. To reduce the heat propagation, a cooling method must be in place. Depending of the design, ESS can be passive air cooled, active air cooled, or liquid cooled. The advantages and disadvantages are explained in these studies [21] [29]. Finally, cooling a battery pack in normal ambient temperatures (20°C) during operation or storage mitigates self-discharge, power, and capacity fade [21].

3.2.6 Battery Model

There are several battery models and some are more complex than others. Incoming students are normally in sophomore and junior year level, thus a simple battery model is enough to teach the basics of a battery behavior with voltage, current, internal resistance and power. A battery model presented by Yang et al. is used, where P_{batt} is a function of V_{oc} (voltage open circuit), I_{batt} (battery current), R_{batt} (internal resistance of the battery) [28].

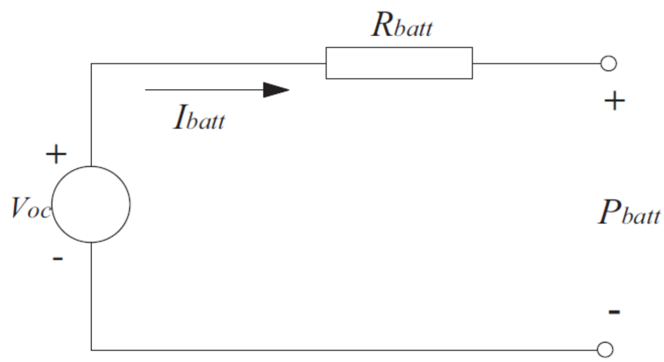

Figure 3-2: Basic battery model
(From Yang, et al., Comparison of power-split and parallel hybrid powertrain architectures with a single electric machine: Dynamic programming approach, *Applied Energy*, 168, 2016: pages 683-690, used under Fair Use, 2018 [28]

The battery model can be analyzed using Ohms law. A resistor capacitor pair is needed to model the transient response of a battery. Several studies have shown different modeling techniques [27] [29] [30], but for the purpose of this thesis a simple basic battery model is enough. By using this electrical circuit to model a battery, the internal resistance could be determined by providing a load on the open terminals.

3.2.7 Battery Management System

As previously explained, lithium ion cells are connected in series or parallel to provide a useful voltage or power depending on the application. When cells are connected in series or parallel, capacity differences may occur even if cells are rated at the same capacity. Cells in series with mismatched capacity can reduce the performance of the whole pack. The reduced performance occurs because the weakest cell limits the overall performance of the pack [21]. The same situation occurs when charging, given the weakest cell could be overcharged. Overcharge and under discharge is extremely dangerous for a battery pack thus monitoring each series cell voltage individually is necessary to ensure safe operation [21] [32].

The main component used on battery packs is a battery management system (BMS) to protect the cells from under and over voltage. BMS monitors the voltage of each cell to ensure these are charged equally. During charge, the moment one cell group is fully charged, the BMS discharges at a small rate to equalize that cell group with the next highest cell group. The BMS monitors these cell groups and ensures all reach the same maximum voltage [33]. This process is called charge balancing and it ensures all battery cells have the same voltage to provide the maximum power allowable by the system. Battery management systems from different manufactures have the ability to be controlled through a controlled area network (CAN) and provide specific limitations but are more expensive.

3.2.8 Wire and Fuse Sizing

HEVs and EVs have several different components to electrify the vehicles. As electrical systems become more complex, wire sizing and fuse sizing becomes imperative for safety. Wire sizing corresponds to the selection of the correct wire gauge to meet current draw, voltage, and temperature requirements. An undersized wire may melt the insulation and short circuit the system. Oversized wire adds cost, weight, and complexity in routing. Therefore, a steady state and transient model developed by Nelson et al. is used to size wires [34] [35]. These models were developed to help HEVT when designing LV and HV systems.

A fuse is an electrical safety device that protects the circuit from overcurrent. A fuse acts as a sacrificial device to interrupt the flow of current and protect the wire or components. Fuses are rated for both direct current (DC) and alternating current (AC). For vehicle applications, the rated voltage and current are in DC. Fuses come in different shapes and for different applications. The voltage rating must never be exceeded for safety reasons. The current rating is the continuous current allowable that a fuse can hold. However, temperature and transient current are culprits to blow a fuse. Manufactures provide a specification sheet for fuses and the I^2t curves that explain the amount of time a fuse blows depending on the current. Temperature effects cause de-rating for a fuse. At higher temperatures (80°C) the fuse performance could be decreased by 30%, reducing the allowable continuous current [34]. Transient current behaviors such as pulses can affect fuses. Overall, the fuse current rating should be lower than the wire ampacity to reduce the event of a short circuit.

3.3 Motor Systems

Electric and hybrid vehicles are a promising solution to reduce energy consumption in the automotive industry. To reduce energy consumption, electric machines (EM) are used to both propel and brake [36]. EMs could be either DC or AC motors. Permanent magnet synchronous motors (PMSM) are mostly chosen today due to advancements in power electronic converters [37] [38]. PMSM are also AC motors.

One main technology already implemented in automotive industry is regenerative braking. Regenerative braking is used to improve the energy efficiency and driving range in EVs and HEVs [28]. Regenerative braking is the process of when the electric motor can act as an electric generator to convert kinetic energy into electric energy and store it into the ESS for future use. There are several studies that discuss regenerative braking, but this thesis concentrates on the learning of three-phase AC electric motors and the loading mechanism to bench test AC electric motors.

3.3.1 AC Motors and Motor Drive

AC motors are the dominant motor technology used today. These can be classified as single-phase or three-phase [23]. Three-phase AC motors are concentrated on this literature review given HEVT used three-phase AC motors in the past twenty years. Likewise, these types of motors are the most common motor used in commercial and industrial applications [23]. Three-phase motors have a number of individual wound coils constructed internally. The wound coils are wired either in series or parallel to produce three different windings, normally known as: Phase A, Phase B, and Phase C.

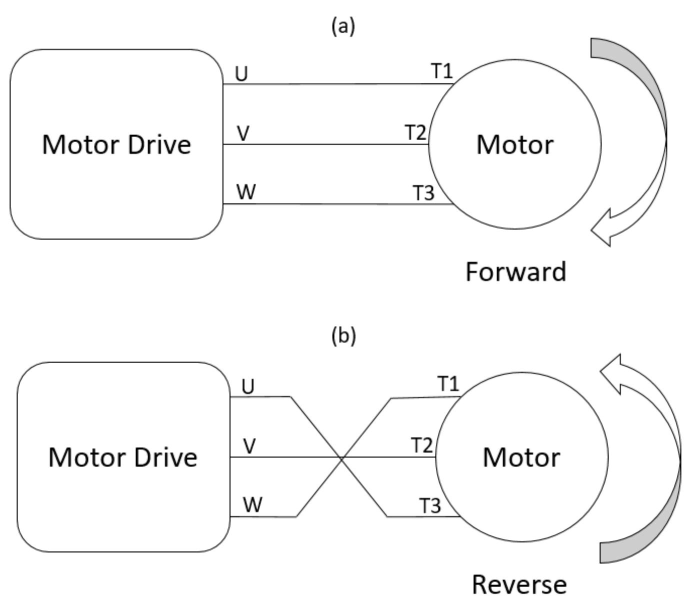

Figure 3-3: (a) Forward three-phase motor connection and (b) reverse three-phase motor connection.
Created by author using knowledge from Petruzella et al. [23] and InMotion U.S.

Depending on the three-phase connection to the motor drive, the motor may spin forward or backwards. It is standard practice to determine the direction of rotation before making lasting connections. As seen in Figure 3-3, just interchanging two phase leads of the motor can reverse the direction. The main components of a motor are the stator, the rotor, the windings and the case. For an AC motor, the rotor rotates due to a magnetic field created by the stator [23].

To control an AC motor, a variable-frequency drive (VFD) system is needed. This controller is also known as the motor drive or motor inverter. The motor inverter converts electricity from DC to AC to drive a motor. When a motor drive controls a motor, the motor converts electrical energy into mechanical energy to spin the shaft. According to Petruzella et al., there is a direct relationship between armature current and motor torque as well as armature voltage and motor speed [23]. Motors are rated with a base speed. Base speed is the speed of the motor at the rated voltage and rated current where it produces the maximum power output. When motor speed is above the base speed, the torque starts to decrease to hold a constant power. Below is an example of a torque-speed curve behavior and the relationship.

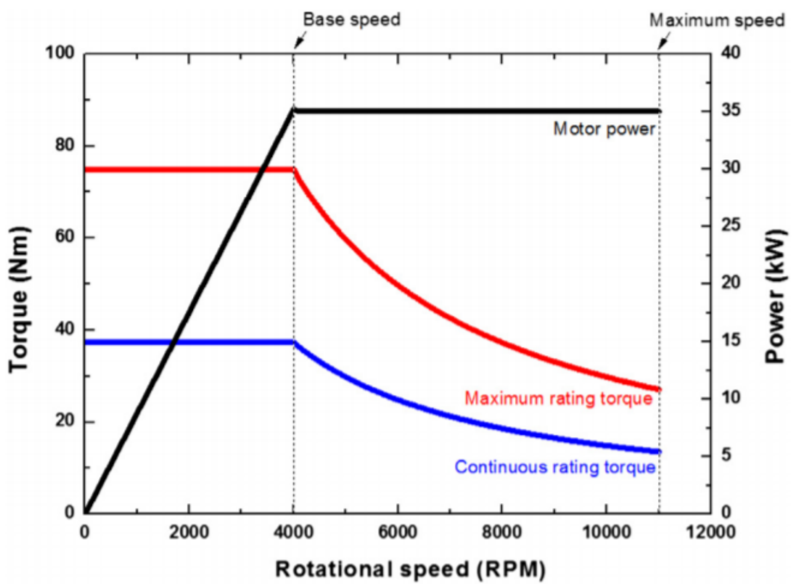

Figure 3-4: Ideal motor torque speed curve and motor power speed curve (From Lim, et al., Thermal performance of oil spray cooling system for in-wheel motor in electric vehicles, *Applied Thermal Engineering*, 63, 2, 2014: 577-587), used under Fair Use, 2018 [39]

3.3.2 Motor Dynamometer

A dynamometer is a device used to test different rotary machines. A dynamometer consist of a shaft coupling and a controllable load mechanism, normally able to command either speed or torque. Although there are several types of dynamometer, a motor dynamometer is chosen to relate the learnings to HEVs, EVs, and motor systems. In addition, the dynamometer setup must introduce the concept of regenerative braking. In general, a motor dynamometer consist of a motor acting as a driving mechanism and a motor acting as the generator to load the system. Both motors must each have a separate motor controller, known as the motor drive, to control and command torque or speed to each motors. Between the couplings of both motors, a torque sensor is needed to monitor both torque and speed of the driving motor. The motor acting as a generator must always be on the opposite setting compared to the driving motor (i.e. generator in speed mode and motor in torque mode) [40].

3.3.3 Motor Quadrants

Motor drives could either be single-quadrant or four-quadrant. Single-quadrant drives are known as non-regenerative drives and have no braking capabilities. A four-quadrant drive is able to take the mechanical energy of the motor and convert it into electrical energy, thus braking the motor to return energy to the DC bus. Four-quadrant drives have the capability of going in forward or reverse direction. The four-quadrant drive is determined by motor speed and motor torque [23].

- Quadrant one occurs when the drive provides forward torque and motor speed. This quadrant is known as the normal condition of a motor.
- Quadrant two provides a backwards torque and a forward motor speed. This is known as the regenerative condition when the drive is absorbing power from a load.
- Quadrant three provides backwards torque and backwards motor speed. It is as quadrant one but in the reverse direction.
- Quadrant four provides forwards torque and backwards motor speed. This is as quadrant two but in the reverse direction, known as the regenerative condition.

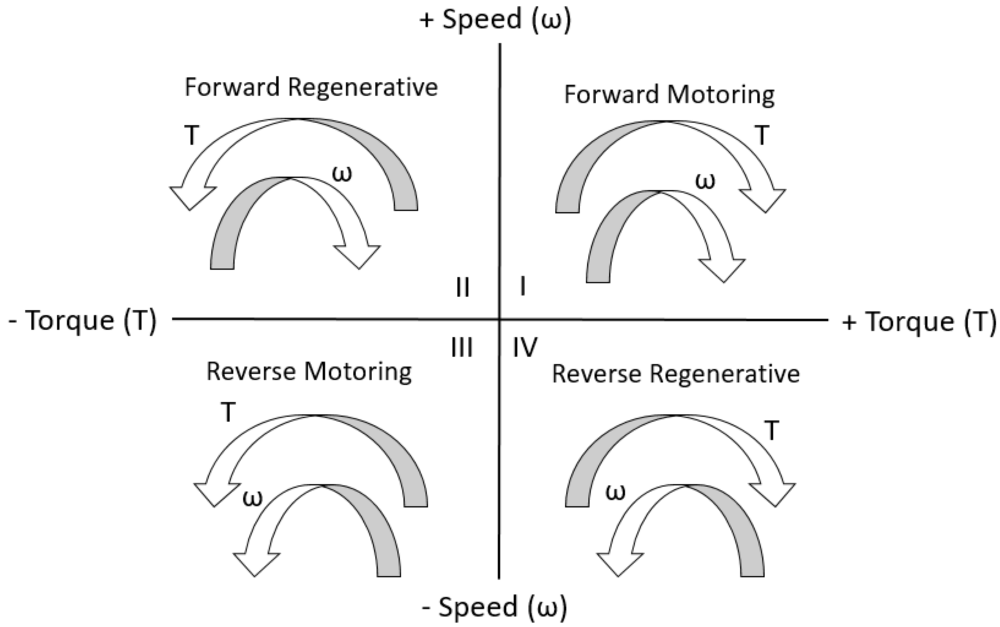

Figure 3-5: Four quadrants motor drive operation
Created by author using knowledge from Petruzella et al. [23] and InMotion U.S.

3.3.4 Relays and Contactor Logic

The electromechanical relay (EMR) is a switch operated by an electromagnet. Relays turn the load on or off by providing power to the electromagnet. Relays have two components: a coil input and a contact output. Relays and contactors have similar behavior, the only difference is that contactors are rated for higher power, normally for HV systems. Contactors are used to reduce the inrush current and prevent a current surge in the system [23]. Normally, controllers such as motor drives have capacitors which should be current limited during start-up to reduce the surge current. This is known as the pre-charge system. Normally, pre-charge systems are created with a pre-charge resistor or an internal pre-charge circuit.

The main goal of the contactor in this thesis application is to use it by energizing the coil input with a low voltage source to control and close the contact to power the load to allow the controller capacitors to charge. When selecting a contactor, ensure it is AC or DC rated depending on the application.

3.4 Summary

The literature review consisted of an introduction of knowledge to analyze the onboarding process and knowledge transfer. To improve it, two hands-on supplemental projects are generated and explained in the next sections to introduce the electric layout of a hybrid vehicle to incoming students joining HEVT. Several studies are researched to understand the behavior of lithium ion batteries and the safe components needed when building an LV ESS. Likewise, motor systems and dynamometer setup is researched to understand the basics of AC three-phase motors. Chapters 4 and 5 correspond to the design, chosen components, and experimental setup of the LV ESS and LV motor dynamometer.

4 Chapter – Low Voltage Energy Storage System

From an automotive stand point, hybrid vehicles with a battery pack less than 60 V peak are considered low voltage. The energy storage system is built as low voltage for safety and simplicity compared to high voltage systems.

The ESS hands-on supplement content contains many tasks HEVT must complete when building an ESS in a hybrid vehicle. The hands-on project introduces battery system requirements, matching to load, energy and power. The project goes over electrical system design, voltage/current, series/parallel cells, cell connections, insulation, wire and fuse sizing, and clearance. There also exists a mechanical design for support structure, module compression, isolation enclosure and venting. Control systems have a role in the project: the control of contactors, battery management systems, testing and data acquisition. In addition, a simplified battery system model development is needed. Finally, the project goes over documentation: project documentation, assembly/disassembly procedures, schematics and specification sheets.

4.1 Energy Storage Simplified System Overview

The LV ESS is intended to be a bench top component to be used as a power supply for a low voltage motor demonstration system. The system should be built to meet HV rules and to train the next generation of student team members that participate in the next AVTC. A high-level system overview is shown in Figure 4-1.

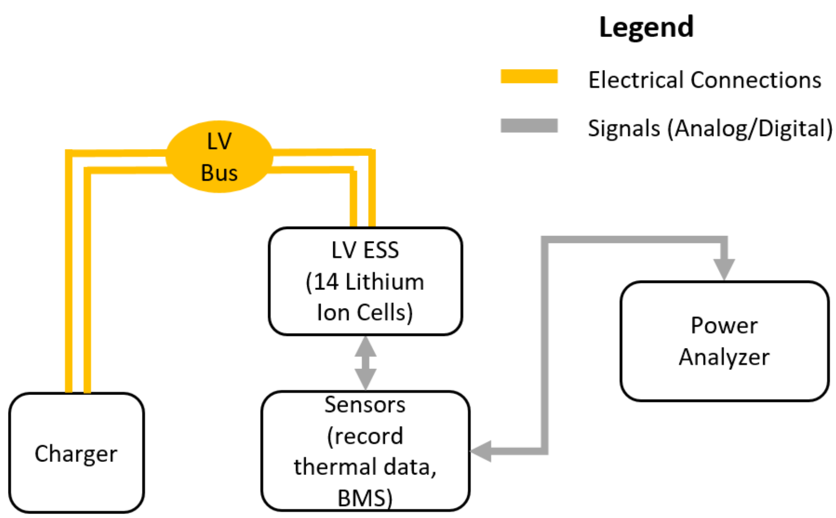

Figure 4-1: Simplified diagram of LV ESS

The LV ESS consist of 14 lithium ion cells connected in series to reach a nominal 52 V. The maximum voltage of the ESS is 58.8 V and the low voltage cut-off is 35 V. Each lithium ion cell is connected to a BMS to ensure each cell does not go over 4.2 V. In addition, a temperature sensor is added to monitor thermal data. The charger converts AC power to DC power to charge the LV ESS. The charger is a constant current (CC) and then constant voltage (CV) device. To monitor the DC voltage of the LV ESS, a power analyzer is used to measure cell voltages, current demand and power demand.

A full LV ESS design is developed using Siemens NX 10. As a bench top testing project, is important for the LV ESS to be moveable and light for a person to carry. During the design process, the layout is iterated many times to address component ratings and clearances, space constraints, and wire routing. The preliminary design of the LV ESS is shown in a CAD model and Figure 4-5 shows the final design as built.

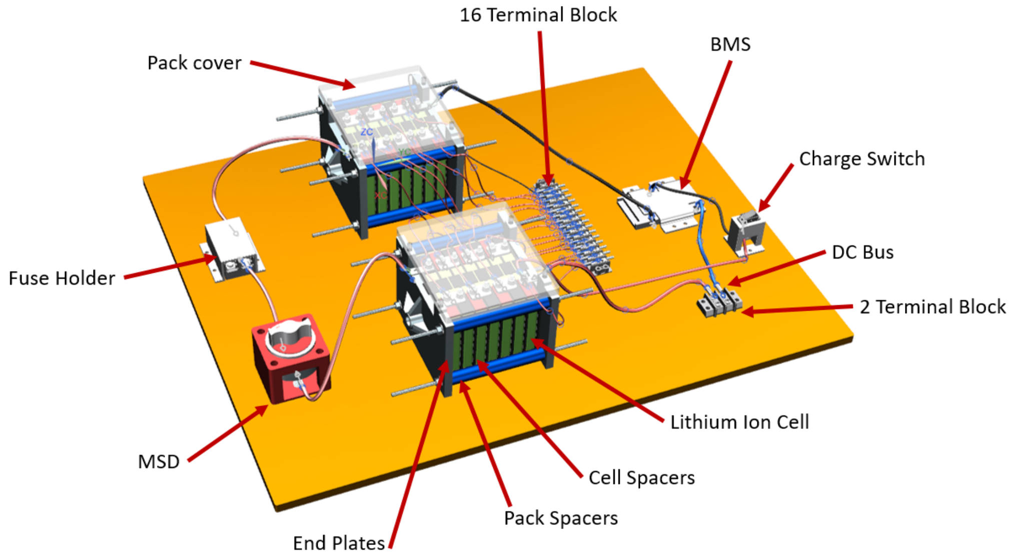

Figure 4-2: 3D Preliminary CAD model of LV ESS

The main overhead materials used to fully finish the system are: plywood, bolts, nuts, washers, lock washers and custom 3D printed mounts. The next section goes into the design and selection of the main components for the LV ESS.

4.2 Component Selection

This section describes the main components in creating the LV ESS. Components include the lithium ion cells, the MSD, the BMS, the charger, charge switch, voltage display, and the wire and fuse sizing.

Before selecting components for the LV ESS, the continuous and peak current demand of the LV ESS must be determined. Although the 5 Ah lithium ion cells are able to discharge at 20C (i.e 100 A) [41], sizing components and wiring to sustain that much current draw increases cost and design complexity. Therefore, the continuous and peak current demand of the motor drives are used to size wires, fuses and the voltage rating of the LV ESS. The motor drive continuous current is 30 Arms and the peak current is 70 Arms. Reference Table 5-2 for all detailed specifications of the motor drives. The operating motor drive voltage is 33-63 VDC [42]. To decrease system complexity and ensure available components in the market, a 30 Arms continuous is chosen. The nominal power capability of the system is thus 1.5 kW. Note the current used to size components is the motor drive DC input current.

4.2.1 Lithium Ion Cells

The lithium ion cells were donated by a Virginia Tech Ph.D. student that cycled and tested lithium ion cells. The prismatic cells came with all required hardware such as washers, lock-washers, nuts, cell spacers and end plates for each cell. In addition, the pack end-plates with spacers were donated. The lithium ion cell specifications are shown in Table 4-1.

Table 4-1: Cell specifications for LV ESS

Cell Specifications	
Cell type	Prismatic type
Positive/Negative Terminal	M5 stud
Rated capacity	5 Ah
Nominal voltage	3.7 V
Max voltage	4.2 V
Min voltage	2.5 V
Max temperature	60°C

Cell series connections are required to build an LV system. When cells are connected in series, the voltage is increased by the amount of cells in a series connection. 14 cells in series is the maximum allowable connections to have peak voltage less than 60 V. By using 14 cells in series, the LV ESS nominal voltage and energy capacity is 52 V and 5 Ah respectively. Thus, the total LV ESS energy is 260 Wh. In automotive industry, ESS are depleted to approximately 20% SOC and charged to 90% SOC to prolong the life and discharge/charge cycles of the battery pack. As seen in the results section 6.1, when the battery pack is depleted at 1C (i.e. 5A) and the load is cutoff when battery pack is at 42 V, the run time is approximately 52 min and 234 Wh of energy is depleted out of the battery. Energy capacity is an important consideration for sizing and ESS design. In this thesis, 5 Ah lithium ion cells are used due to availability.

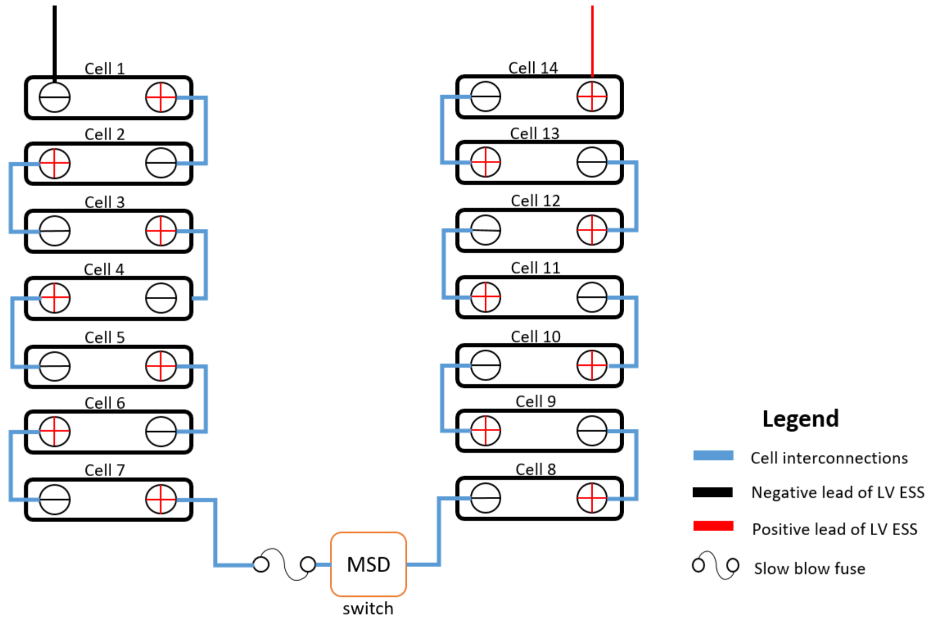

Figure 4-3: Cell interconnection diagram for LV ESS

The design chosen for cell interconnections is two battery packs of seven cells in series. The spacers between the end plates were manufactured to fit exactly seven cells in compression. By having two banks of seven cells, an MSD with a slow blow fuse can be added to the circuit for safety precautions. This also mimics the HEVT practices for building HV ESS. In addition, cells can air cool passively with the ambient temperature. There are cell spacers between each cell to provide passive air cooling. Prior to making the interconnections between cells, it is important to match the voltage for each lithium ion cell. This guarantees the LV ESS is balanced once it is fully built.

4.2.2 Manual Service Disconnect

The main requirements for the MSD is to be a manual on-off switch able to have a key for lockout and tagout. There are two main options for an MSD selection. Below are shown both MSD with the advantages and disadvantages.

Table 4-2: MSD selection comparison

MSD Description	Specifications		Advantages	Disadvantages
Blue Sea Systems 6006	Nominal voltage	48 VDC	Lockout/tagout operable Withstand battery voltage VDC Withstand battery current ADC Comes with mount	None
	Continuous current	300 A		
GIGAVAC HBD21AA	Nominal voltage	1000 VDC	Lockout/tagout operable Withstand battery voltage VDC Withstand battery current ADC	Overdesigned for LV ESS
	Continuous current	200 A		

The chosen MSD is the Blue Sea Systems 6006. This manual switch is able to operate at nominal 48 VDC with a continuous current rating of 300 A. The most important reason to select this manual switch is due to an isolating cover to protect the rear contacts. Refer to the instructions and specifications for installation [43].

4.2.3 Battery Management System

Several types of battery management systems exist in the market. Normally, these are CAN controlled and are able to set different types of limits to each cell (voltage, temperature, current draw). CAN controlled BMS have several configurations but are definitely the most expensive. In the market, a normal CAN controlled BMS averages $450. The Orion Jr BMS is a good example and is able to meet all requirements for the LV ESS [44]. However, the LV ESS hands-on supplement is a project to teach incoming students about battery systems and expensive materials are not required for this setup. Through research, a specific 14 lithium ion cell BMS is found and sold by Vruzend. This BMS is able to meet all LV ESS requirements for $34. The Vruzend BMS specifications are Table 4-3.

Table 4-3: BMS specifications for LV ESS [33]

Lithium Ion BMS Specifications	
Model number	BMS5230
Number of cells	14
Max cell voltage	4.2 V
Min cell voltage	2.5 V
Max rated discharge current	30 A
Charging voltage	58.8 V
Max rated charging current	15 A
*Balance current	50 mA
Operating temperature	-15ºC to +45ºC
Board dimensions	10.9 cm x 5.9 cm x 0.9 cm

*Charger need to be connected to enter balancing mode

The Vruzend BMS is not CAN controlled but is able to limit cell voltage by itself. The BMS5230 BMS has a discharge wire, a charge wire and a battery negative wire. The discharge wire is known as the P-, which connects to the negative lead of the load. The charge wire is known as the C-, which connects to the negative lead of the charger. The B- connects to the negative lead of the battery pack. There are 15 balancing wires. The first balancing wire is black and connects to the negative lead of the battery pack. The other 14 balancing wires connect to the positive cell stud of each cell. By selecting this BMS, the maximum discharge current allowable is 30 A for the LV

ESS. A diagram from Vruzend is shown in Figure 4-4 regarding the cell connections. Follow the installation instruction for more information [45].

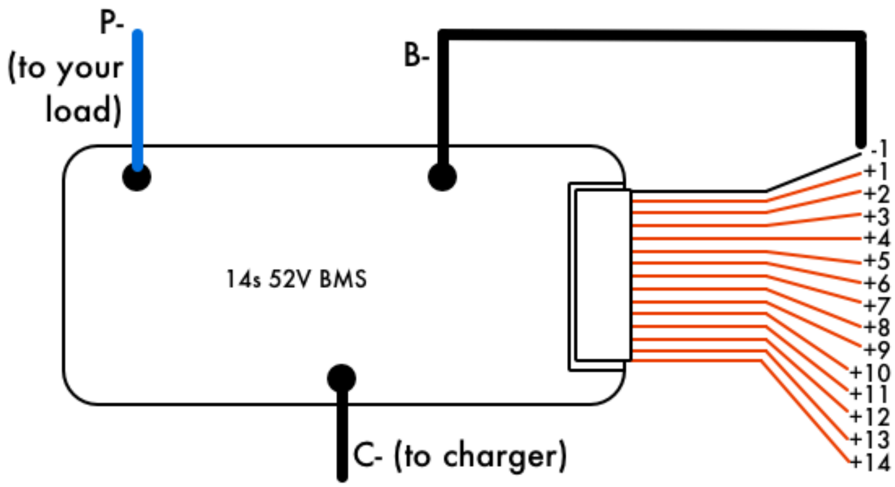

Figure 4-4: 14s BMS diagram connection [33]
used under Fair Use, 2018

4.2.4 Charger

The lithium ion batteries should be charged at a 1C current for battery health. The lithium ion cells are 5 Ah, meaning that a CC-CV charger providing a maximum voltage of 58.8 V and a maximum current charge of 5 A is desired. The chosen charger is a 52 V nominal lithium ion battery charger from Vruzend. This charger is chosen due to price comparison compared to other chargers in the market. The charger specifications are shown next.

Table 4-4: Charger specifications for LV ESS [46]

52 V Lithium Ion Battery Specifications	
Model number	charger523
Full charge voltage	58.8 V
Charging current	3 A
Charger power rating	180 W
Charging profile	CC-CV
Input	110-240V AC 50/60 Hz
Cooling fan	Yes, installed
DC Charging connector	5.5 x 2.1 mm male barrel connector
AC wall connector	2-prong USA plug
Physical size	2″ x 3″ x 6″

The 52 V nominal lithium ion charger has a charging current of 3 A, lower than 1C. Charging a battery pack with a lower C-rate does not provide any downside for battery health. The only difference is the amount of time it takes to fully charge the battery pack. A comparison using different charge rates in the LV ESS is displayed in the Table 4-5.

Table 4-5: Bulk charge rate comparison and time result

C-Rate	Battery Capacity (Ah)	Charge Current (A)	Time to Charge Battery (Min)
1	5	5	60
0.6	5	3	100
0.5	5	2.5	120

As seen in Table 4-5, when charge rate decreases, the time to charge increases. Note only the bulk charge occurs at CC, in the charger phase, at maximum current. Refer to Figure 6-7 for charging results of the LV ESS. The 52 V lithium ion battery charger meets all LV ESS requirements. A 5.5 x 2.1 mm female barrel connector is acquired to connect directly to the positive lead of the ESS and to the negative charge lead of the BMS. Refer to the LV ESS wiring schematics in Low Voltage Energy Storage System Schematics. Connector C3 is the female barrel connector.

4.2.5 Charge Switch

To initialize the charging process, a manual rocker switch is selected for the user. The switch acts as a verification step to ensure all connections have been made in the LV ESS before the charging process starts. Since the charger provides a peak voltage of 58.8 V and a current of 3 A, the selected switch must meet those requirements. The selected rocker switch is a 48 VDC nominal rated at 6 A. This rocker switch is a double-pole single-throw (DPST), meaning that both positive and negative leads are be controlled by the switch [47].

4.2.6 Voltage Display

A voltage display is acquired for the LV ESS for safety and storage purposes. As explained in Section 3.2.5, batteries self-discharge over time. The voltage display is an easy way to determine whether the battery pack is at lower voltage cut-off (i.e. 35 V). There are several types of voltage displays but the main requirement is to read up to 60 VDC. The chosen voltage reader is able to read voltage, current, power, and energy. To read current, a 75 mV – 100 A shunt is used. Table 4-6 provides the voltage display specifications.

Table 4-6: Voltage display specifications for LV ESS

Bayite LCD Display Digital	
Voltage test range	6.5 – 100 VDC
Current test range	0 - 100A
Active Power test range	0 – 10 kW
Energy test range	0 – 9999 kWh

4.2.7 Wire and Fuse Sizing for LV ESS

HEVT faculty advisor, Dr. Douglas Nelson, developed an AAE curriculum module for wire sizing and fuse sizing [34]. This module has been used to generate a general transient thermal model for peak current to find the temperature of the wire with a known continuous current draw. The general transient model solution is seen in the following equation.

$$T_{wire} = T_{amb} + (T_{init} - T_{amb})e^{-\frac{t}{tau}} + (I^2 R'_{el} R'_{th})\left(1 - e^{-\frac{t}{tau}}\right) \quad (1)$$

Where T_{wire} is the temperature of the wire, T_{amb} corresponds to the ambient temperature, T_{init} is the wire temperature at steady state, t is the time, tau is the thermal time constant of the wire, I is the peak current, R'_{el} is the wire electrical resistance, and R'_{th} is the wire thermal resistance. More information can be found in a study made by Marquez and Nelson et al. [35] [34]. Equation 1 can be rearranged to determine the time the wire temperature reaches the insulation temperature.

To size the main wire, all wires must be automotive standard wires. These have insulation temperature ratings of 90, 105, and 125 ºC. The greater the insulation temperature rating the more expensive the wire is. Since the LV ESS is to be tested in a controlled environment at 25 ºC, an insulation temperature of 90 ºC is sufficient for the application. Below is a table with thermal wire modeling of the selected wire size with known initial conditions.

Table 4-7: Thermal wire modeling results at different conditions

Application	Ambient Temperature (ºC)	Insulation Temperature (ºC)	Continuous Wire Current (A)	Peak Wire Current (A)	Wire Size (AWG)	Time (s) for $T_{wire} = T_{insulation}$
DC battery power leads	25	90	30	70	12	4.96
	35	90	30	70	12	0.48
	25	90	30	32	12	Inf.
	35	90	30	32	12	16.65
	25	90	30	70	10	51.21
	35	90	30	70	10	35.79
	25	90	30	32	10	Inf.
	35	90	30	32	10	Inf.
DC battery charge leads	25	90	3	3.5	20	Inf.
	35	90	3	3.5	20	Inf.

The selected wire gauge for the power leads is 10 AWG. Although 12 AWG would suffice for a controlled temperature room, it could not be enough if the LV ESS is tested outside at temperatures of 35 ºC. Also, if the BMS is bypassed and the pack is discharged at a peak current of 70 A, the 10 AWG wire takes approximately 36 seconds to reach the wire insulation temperature rating. To protect the wire and the component, a fuse is used which is further explained later. The wire gauge for the charge leads could be as small as 20 AWG. If a bigger wire gauge is chosen for the charge leads, the temperature of the wire is not going to reach the insulation temperature. The most common reason to choose a bigger wire gauge is to keep a symmetry along the system.

There are two fuses required when building an LV ESS. The first is the mid-pack fuse to protect the whole battery pack in case of high loads. The second is the charge fuse to protect the pack from current faults during the charging process. The mid-pack fuse chosen is a 30 A fuse rated at 300 VDC, slow blow. The slow blow specification allows more power through the fuse and prevents from opening during high short time current spikes. Since low voltage automotive fuses are rated up to 32 VDC, HV fuses are considered. Littlefuse has a family of low current (LC) HEV fuses. The fuse termination chosen is cartridge to use on a fuse holder. Note the fuse holder must match the system voltage (LV ESS) and the fuse current rating.

The charge fuse is difficult to select. Due to the low current supplied during charging, fuses become limited on the market for voltage ratings of 60 VDC. The only types found are glass fuses able to withstand 125 VDC with several current ratings. The glass fuses are normally fast-acting, meaning the fuse blows after going above the rated current. The chosen charge fuse is a glass fuse rated at 125 VDC and 3.5 A, fast acting.

4.3 Overall and Detailed Design of Energy Storage System

All chosen components meet all requirements to build the LV ESS. A bill of materials (BOM) is presented in Table 4-8 and Figure 4-5 shows the final design as built.

Table 4-8: Bill of Materials of LV ESS

QTY	Part #	Description	Application
14	N/A	Prismatic lithium ion cells	Energy source of the battery pack
12	N/A	Bus bars	Cell interconnection
16	N/A	Cell spacers	Space cells for thermal management
4	N/A	End plates	Compression plates to reduce thermal expansion
8	N/A	Pack spacers	Spacers for compression end plates
8	N/A	Stud bars	Compression of battery pack
28	N/A	M5 nuts	Cell terminal nuts
28	N/A	M5 washers	Cell terminal washers
28	N/A	M5 lock washers	Cell terminal lock washers
1	0HEV030.ZXC	30 A HEV fuse	Slow blow mid-pack fuse
1	N/A	30 A fuse holder	Holds and protects mid-pack fuse
1	611-DF62J12S2AQA	Rocker On-Off 48 V switch	Charging rocker switch

QTY	Part #	Description	Application
1	7527K82	300V AC/300V DC Terminal Block, Two 30A Circuits, 9/16" Center-to-Center w cover & marker strip	Terminal block for DC bus
1	7527K75	300V AC/300V DC Terminal Block, Sixteen 30A Circuits, 9/16" Center-to-Center w cover & marker strip	Terminal block for BMS connections
1	6006	Blue Sea Systems m-Series Battery Switch, 2 Position, On-Off, 300A, 48V	Manual Service Disconnect (MSD)
1	N/A	5.5 x 2.1 mm female connector Vruzend	Charging female connector for 52V charger
1	N/A	52V Lithium-ion battery charger (3 A)	Charger for LV ESS
1	N/A	52V 14s Battery Management System (BMS)	BMS for LV ESS
10 ft.	N/A	10 AWG (90 ºC) red wire	Wire for power leads
10 ft.	N/A	10 AWG (90 ºC) black wire	Wire for ground leads
20 ft.	N/A	20 AWG (90 ºC) red wire	Wire for balancing wires
10 ft.	N/A	20 AWG (90 ºC) black wire	Wire for balancing wires
1	F2463-ND	Fuse glass 3.5A 250VAC 125VDC	Charge fuse
1	F1468-ND	Inline fuse holder 350V, 10A	Inline fuse holder for charging circuit
1	N/A	bayite DC 6.5-100V 0-100A LCD Display Digital Current Voltage Power Energy Meter Multimeter	Digital voltage reader for battery monitoring
1	N/A	75 mV – 100 A shunt	Device to measure current
15	Panduit	Ring Terminal, 22 – 18 AWG, #10 stud, nylon insulated	Ring terminals for balancing wires
40	Panduit	Fork Terminal, 22 – 18 AWG, #10 stud, nylon insulated	Fork terminals for balancing wires and shunt connections
8	Panduit	Ring Terminal, 12-10 AWG wire, #10 stud hole, nylon insulated	Ring terminals for ground and power leads
1	Panduit	Ring Terminal, 16 – 14 AWG, #10 stud size	Ring terminal for charger switch
4	Panduit	Ring Terminal, 12 – 10 AWG, 3/8" stud size, nylon insulated, standard package.	Ring terminals for shunt and MSD
2	Panduit	Loose Piece Disconnects, 22-18 AWG	Disconnects to charge switch
2	Panduit	Loose Piece Disconnects, 16-14 AWG	Disconnects to charge switch
1	N/A	High quality plywood	Base of LV ESS
2	N/A	1' x 1' of polycarbonate	Battery pack cover protection
1	N/A	Roll of Kapton tape	Protect terminal studs from contacting one and other

There is overhead hardware such as bolts and washers to fully complete the LV ESS that are not in the bill of materials. The majority and main components required are shown Table 4-8. The built LV ESS is shown next.

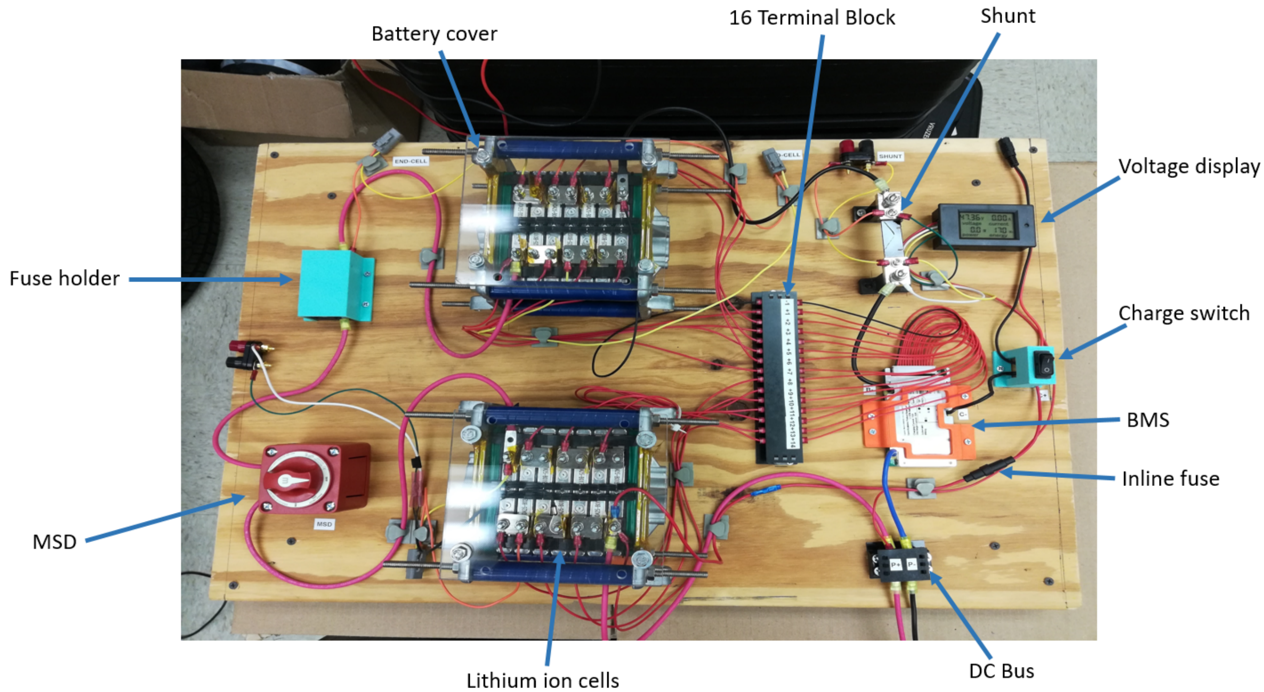

Figure 4-5: Final design product of LV ESS

There are three types of operation in the LV ESS: Charge mode, Depletion mode, and service mode. Each mode is user selectable, so directions must be followed to prevent any safety hazard. The steps to operate each mode are described next.

Charge Mode

1. Ensure that the MSD and the charge switch are off.
2. The DC bus for the load must be disconnected.
3. Connect the charger to the wall and connect the charger to the female barrel connector.
4. Rotate the MSD 45 degrees clockwise to turn it on.
5. Verify the voltage of the pack with the digital voltage reader
6. Turn on the charge switch for the charger to provide power to the LV ESS.

Depletion Mode

1. Ensure the MSD and the charge switch are off.
2. The female barrel connector must be disconnected from the charger.
3. Connect the DC bus to a load (resistors or motor system).
4. Rotate the MSD 45 degrees clockwise to turn it on.
5. Verify the voltage of the pack with the digital voltage reader.

6. The LV ESS is ready to power up a system.

Service Mode

1. Ensure the DC bus and the female barrel connector are disconnected.
2. Rotate the MSD 45 degrees counterclockwise to turn off the LV ESS.
3. Verify the voltage of the pack with the digital voltage reader (a decrease in voltage should happen when rotating the MSD).
4. Remove knob from MSD.
5. Start lockout and tagout procedure.

4.4 Data Acquisition System

HEVT uses a main power analyzer as an instrumentation tool to test and record data for HV ESS. This power analyzer is used as data acquisition for the LV ESS to teach students HEVT tools and programs in the onboarding process. The power analyzer is a Hioki 3390 Power Analyzer capable of using four channels to record voltages up to 600 VDC and four channels to record current either AC or DC. The current sensors are hall-effect sensors able to measure the current flux to determine the current going through a specific wire. The power analyzer has an SD card capable of saving and recording data for later use to perform data analysis.

Other devices for data acquisition systems can be used to monitor voltage and current such as an National Instruments (NI) myDAQ. This is a low-cost data acquisition device that is on the price range of any student laboratory. The downside of the myDAQ system is the low quantity of analog inputs to record cell voltages. Likewise, only the DMM inputs can be used to accurately measure resistance, current and voltage. Resistance is used to measure temperature from a negative temperature coefficient (NTC) thermistor and voltage is used to measure the voltage drop of the shunt. During the construction of the LV ESS, connectors are placed in strategic locations for ease of data acquisition using the myDAQ. On the other hand, the power analyzer does not require external connectors because it has special hook clip voltage connectors rated for 300 VDC and 1A. The connector layout can be seen in Figure 4-6.

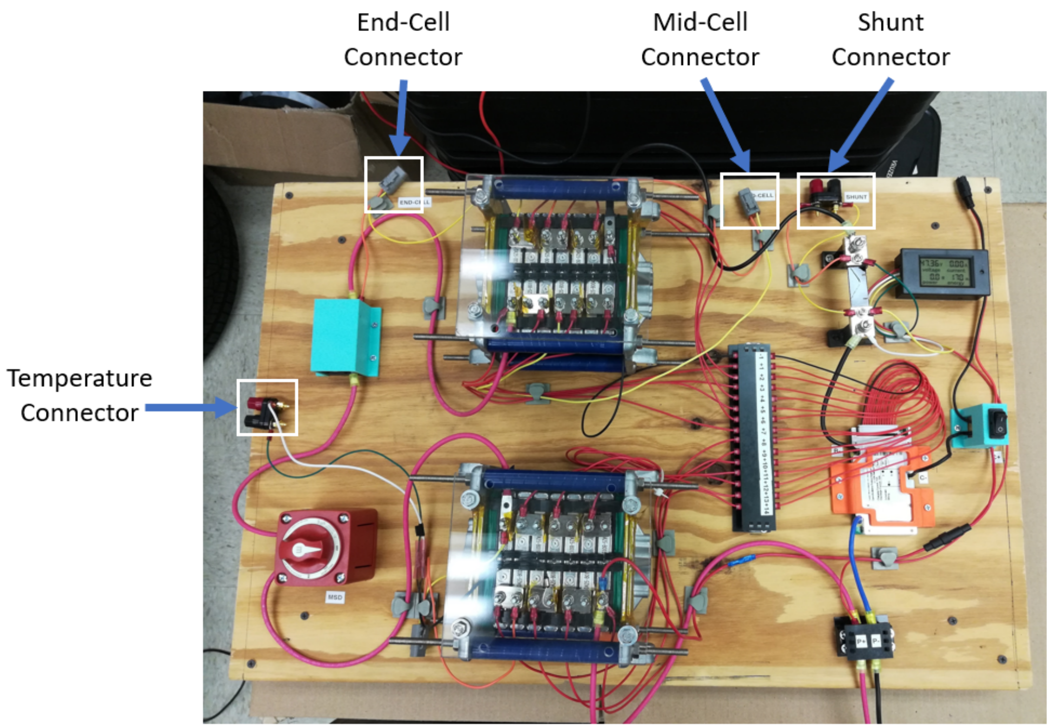

Figure 4-6: Connector layout for myDAQ data acquisition

For both data acquisition devices, computer software is used to process the data. These are explained in the next section.

4.4.1 Computer Software Required

Several software programs are used to process data. These programs are used in the industry and the goal is for the incoming students to become experienced with these programs before students join HEVT for senior design.

Table 4-9. Installed software and purpose

Software	Purpose
CAD NX 10.0	Mechanical design of structure, wire routing, clearance between components.
MS Visio Vesys	Schematic design of components. Document all wire size and fuse size selected for the LV ESS.
MatLab	Math software analysis tool to do data processing.
MS Excel	Math software analysis tool to do data processing.
NI LabView 2017	Record and monitor on real time cell voltage and resistance for shunt measurements.

4.5 LV ESS Model

The basic battery model presented by Yang et al. is used [28]. This model is used to analyze the behavior of the overall pack and the internal resistance. Below is a modified circuit to calculate the internal resistance of a battery.

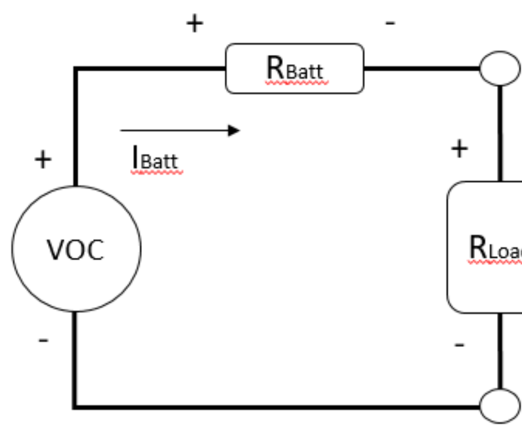

Figure 4-7: Battery model circuit with a load applied
(adapted from Yang, et al., Comparison of power-split and parallel hybrid powertrain architectures with a single electric machine: Dynamic programming approach, *Applied Energy*, 168, 2016: pages 683-690, used under Fair Use, 2018 [28]

Using Ohms and Kirchhoff's law the following equation can be determined.

$$P_{Batt} = V_{oc}\, I_{Batt} - {I_{Batt}}^2 R_{Batt} = I_{Batt}\, V_{Load} \quad (2)$$

Where P_{Batt} is the power demand of the battery, V_{oc} is the open voltage circuit, I_{Batt} is the current demand coming out of the battery, R_{Batt} is the internal resistance of the battery, V_{Load} is the load voltage. Rearranging equation 2 to determine R_{Batt} is the following:

$$R_{Batt} = \frac{V_{oc}\, I_{Batt} - I_{Batt}\, V_{Load}}{{I_{Batt}}^2} \quad (3)$$

Assumptions in this model include no losses or voltage drop due to wire resistance, added switches, wire terminations, shunt resistance, and other wire interconnections. Although these losses are assumed to be very small, a complex system could lead to inaccurate readings. Given the LV ESS is a bench top system with limited wire length and wire connections, it is expected that the calculated internal resistance is within the range compared to testing results by Advance Vehicles in Idaho National Laboratory (INL) [48].

4.6 LV ESS Experimental Setup

To determine the behavior of the LV ESS, a load is generated. The easiest way to generate a load is by using high power resistors to deplete the pack. An external load setup is built as a portion of the experimental setup of the LV ESS. Using Ohms Law to size the external load to be approximately 1C (discharge at 5 A), the resistance of a high-power resistor is determined.

$$V_{ESS} = IR_{Load} \tag{4}$$

Where V_{ESS} is the voltage of the LV ESS, I is the discharge current, and R_{Load} is the resistance of the high power resistor. Using the nominal case, the resistance and power dissipation determined is 10.4 Ω and 260 W. Although there are disadvantages of just using a resistor to load the system due to current drop, it is sufficient because students can learn the basics of circuits. In addition, building the load setup takes considerable less time than other possible solutions.

The chosen high-power resistors are rated for 5 Ω resistors and 225 W for power dissipation. To provide the approximate 1C discharge to the LV ESS, two resistors are connected in series. When resistors are connected in series, the ohm rating and power rating are added. Overall, the load setup is rated at 10 Ω and 450 W for power dissipation. This meets the requirements to load the LV ESS.

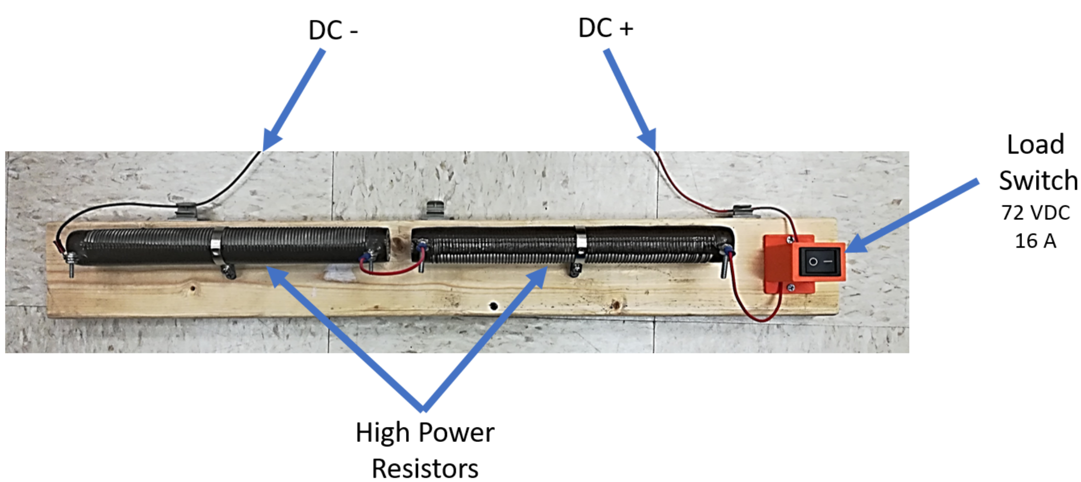

Figure 4-8: Finalized load setup using high power resistors

The setup for load testing starts by connecting the DC leads to the LV ESS. Three hook voltage clip connectors pairs from the power analyzer are used to monitor pack, and cell voltage. Only two voltage channels are used to measure mid-cell and end-cell voltages. These two locations are the extreme scenarios possible and are chosen to monitor the behavior between middle and end cells.

The third voltage channel is used for the battery pack terminals. An AC/DC current sensor is used with the power analyzer to measure the RMS current through the load. The following figure presents a diagram of the load setup.

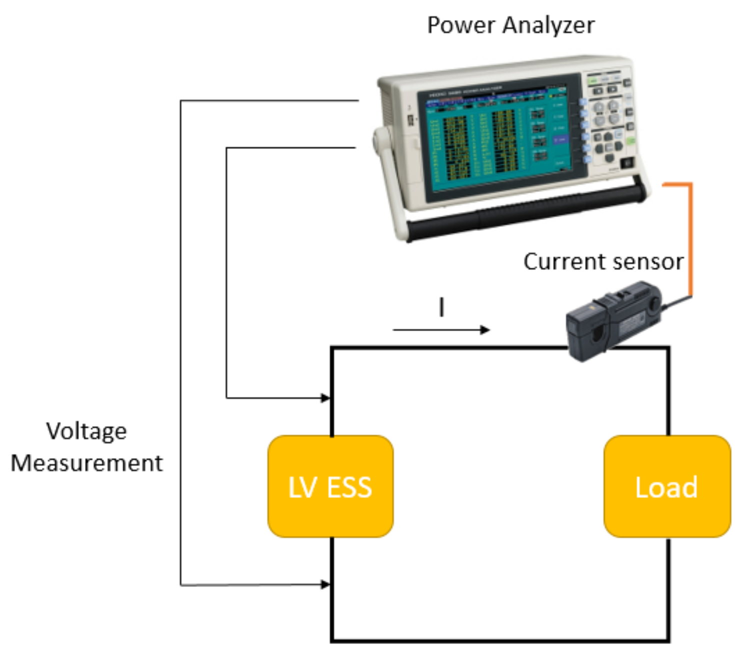

Figure 4-9: Data acquisition diagram for load testing

The load testing setup is also used to determine the internal resistance of the LV ESS. The open circuit voltage can be measured in the battery terminals after a resting period of 15 minutes. Resting period indicates there is no current flow through the battery pack. The goal is to measure V_{oc} when the LV ESS is not loaded, and measure V_{Load} and I_{Batt} when the LV ESS is loaded. The following steps provide a test plan to calculate the internal resistance of the battery pack

1. Instrument the LV ESS with the power analyzer.
2. Connect a hook voltage clip pair to the battery terminals and the AC/DC current sensor to the power analyzer. Do not forget to start measuring. Note the LV ESS voltage should be above 58 VDC.
3. Load the battery pack using the load switch (turn on the load switch).
4. Discharge the LV ESS for approximately six minutes. Note as the lower limit voltage is approached, discharge time should be decreased.
5. Turn off the load switch (no current through the battery pack).

6. Rest battery pack for 15 minutes.
7. Repeat steps 3-6. Note to not deplete the LV ESS beyond 42 VDC
8. Save data to computer for data processing

The setup for charging starts by connecting the charger to the LV ESS. Use the hook voltage clip connectors from the power analyzer to monitor pack, and cell voltage. Only two voltage channels are used to measure mid-cell and end-cell voltages. The other channel is used for the LV ESS. An AC/DC current sensor is used with the power analyzer to measure the charging RMS current. The following figure presents a diagram of the charging setup.

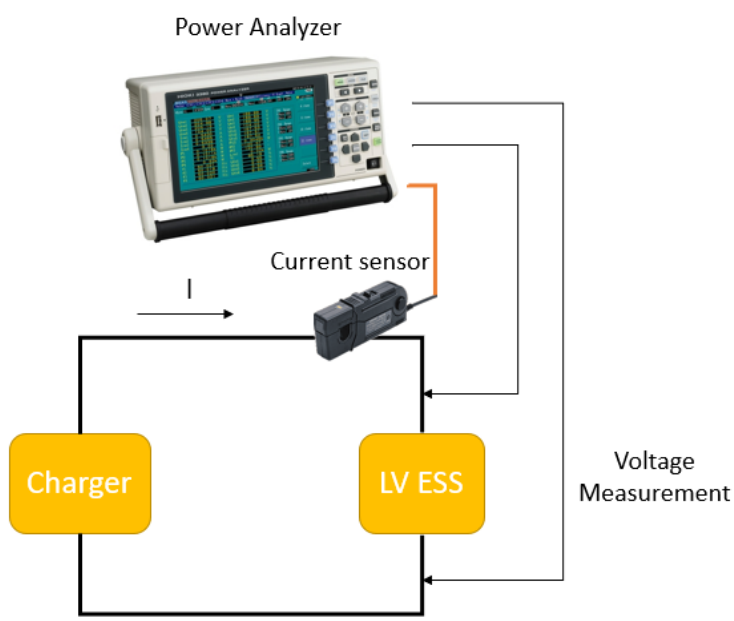

Figure 4-10: Data acquisition diagram for charging

5 Chapter – Low Voltage Motor System Dynamometer

The motor system is based on a system similar to an automotive traction motor system that uses a CAN message torque command, speed command, and monitors motor operation. The completed low voltage motor system can be used as a demonstration load on the LV ESS as a power supply.

The motor system hands-on project content contains many tasks HEVT completes when building a hybrid vehicle. The module introduces motor system requirements, and matching battery power, voltage, and current. The module goes over electrical design, system voltage/current, high current connections, wire and fuse sizing, routing, and clearance. There is also a mechanical design of the motor mount support structure, load/generator torque coupling, and torque load reactions. The project goes over a cooling system to dissipate losses; however simple fan cooling is enough for the system. Control systems have a role in the project: the control of torque command, system enable, testing and data acquisition. Finally, the content goes over documentation: project documentation, assembly/disassembly procedures, schematics and specification sheets.

5.1 Simplified Motor System Dynamometer Overview

The motor system dynamometer is intended to be a bench top component to be used as a learning and demonstration tool for incoming students to learn about motors. The system is built to meet wire clearances and torque reactions. A high-level system overview is shown in Figure 5-1.

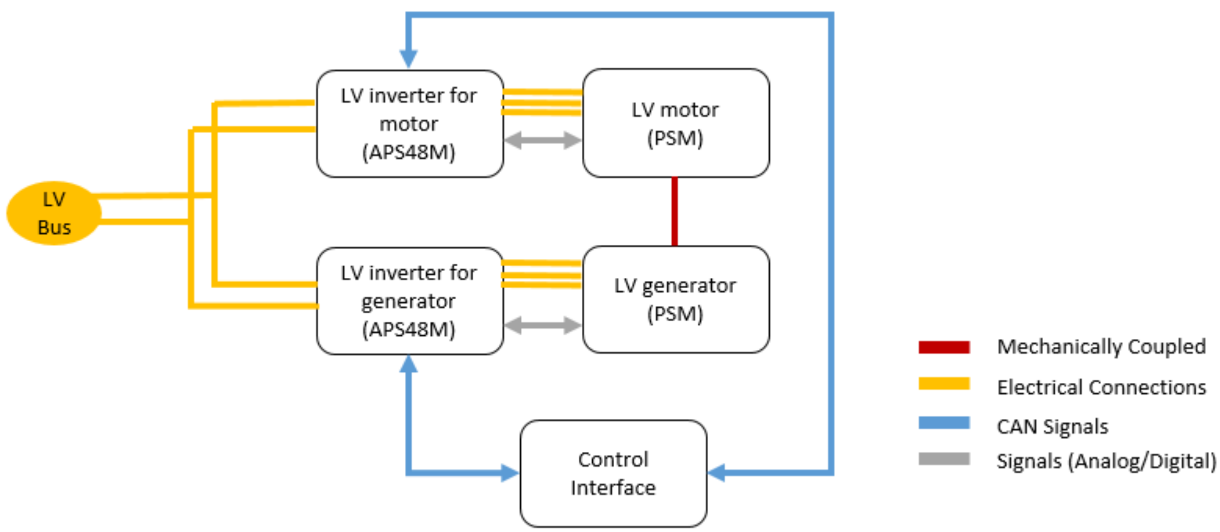

Figure 5-1: Simplified diagram of motor dynamometer system

The motor system dynamometer consists of two motor systems (motor and motor drive) in a closed loop to create a motor dynamometer. The “motor” is the driving unit and the motor loading the system is the “generator”. Both motors have an APS48M inverter that provides variable frequency, voltage, three-phase AC power to motors. The “driving motor” converts electrical power into mechanical power by rotating the shaft. The shaft couples mechanically both the motor and the generator. The generator loads the system and converts the mechanical power into electrical power back to the generator inverter. Finally, the generator inverter returns power to the DC bus. The generator system is controlled in speed mode using a control interface (computer) and the driving motor system is controlled in torque/current mode. To control both motor systems, two

CANcaseXL devices are used to allow CAN communication from the control interface to the two inverter pairs. The final LV motor dynamometer system design is presented in Figure 5-2 to present the layout and main components of the whole system.

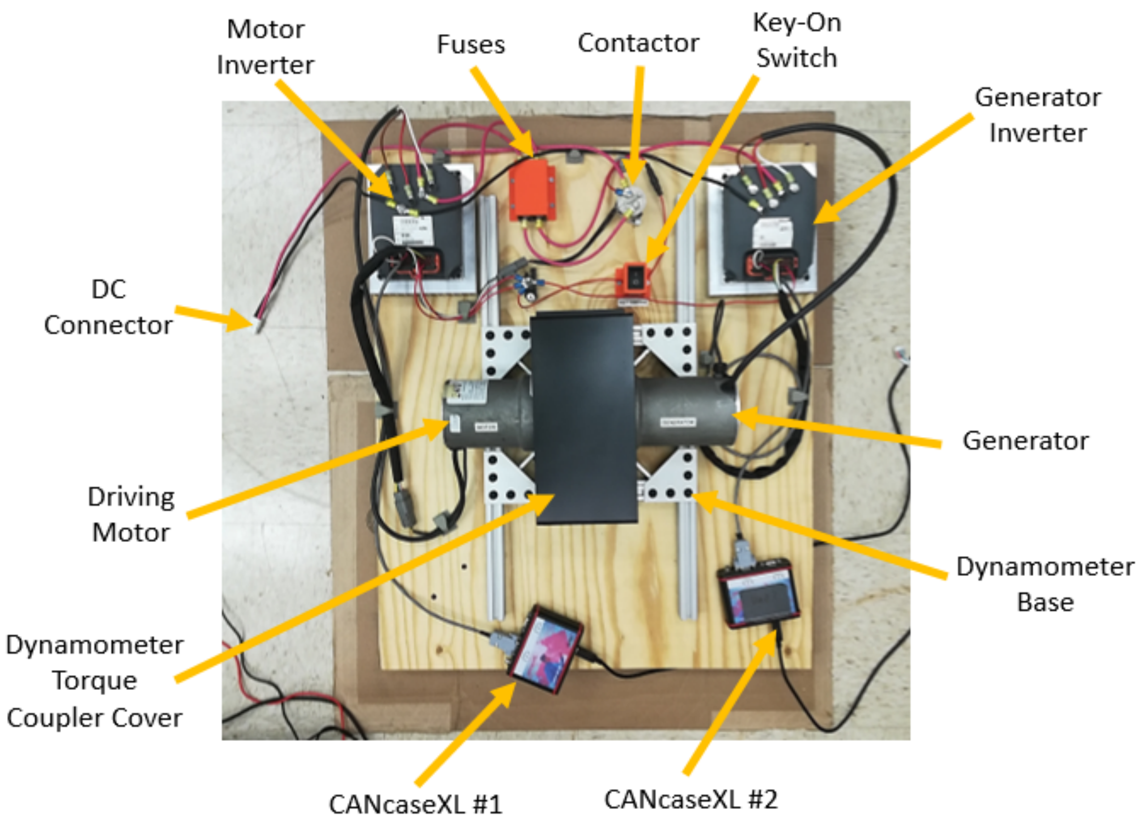

Figure 5-2: Layout of motor dynamometer system components

5.2 Component Selection

This section describes the main components to create the motor system dynamometer. Components include the motors, the inverters (motor drive), the contactor, the coupler connection, and motor mounting.

5.2.1 Motor and Generator

HEVT has developed a relationship with a local motor company, InMotion US, during the EcoCAR 3 competition. InMotion US manufactured and donated the main electric motor for the hybrid Camaro of HEVT. Because of this relationship, HEVT was able to receive two low voltage steering motors for bench testing purposes. Both motors are permanent magnet synchronous AC motor (PSM). AC motors have been recently used as the EMs for HEVT. Therefore, these motors are used for the motor dynamometer setup and the specifications are shown below. Note that other motors could be used in this project if desired.

Table 5-1. Main motor and generator specifications

Application	Motor Model Number	Specifications	
Generator	PSM-C3016-D	Voltage	48 V
		Max radial shaft load	2240 N
		Continuous RMS (1 hr.)	30 A
		Peak RMS (1 min.)	70 A
Motor	PSM-B3015-B	Voltage	48 V
		Max radial shaft load	2240 N
		Continuous RMS (1 hr.)	15 A
		Peak RMS (1 min.)	35 A

The torque-speed and current-speed curves of both motors are presented in the next figures by courtesy of InMotion US.

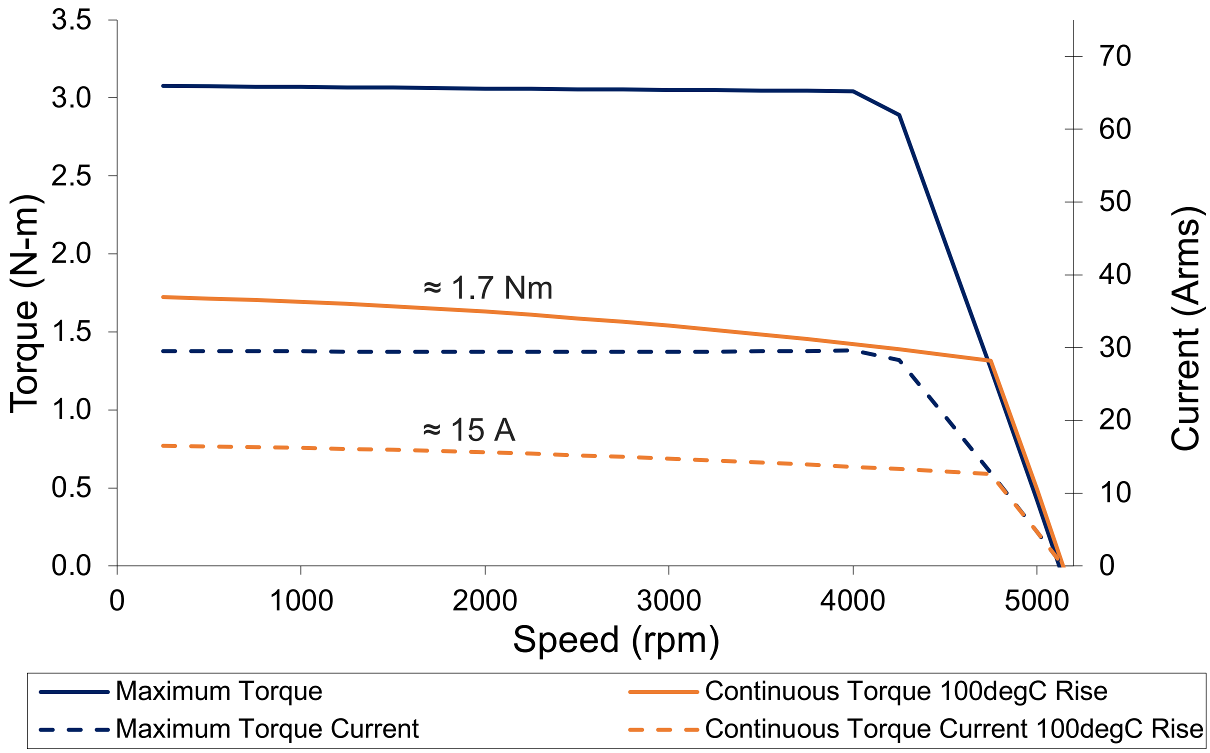

Figure 5-3: Torque/current-speed curve of driving motor (B3015-B) at 48 VDC

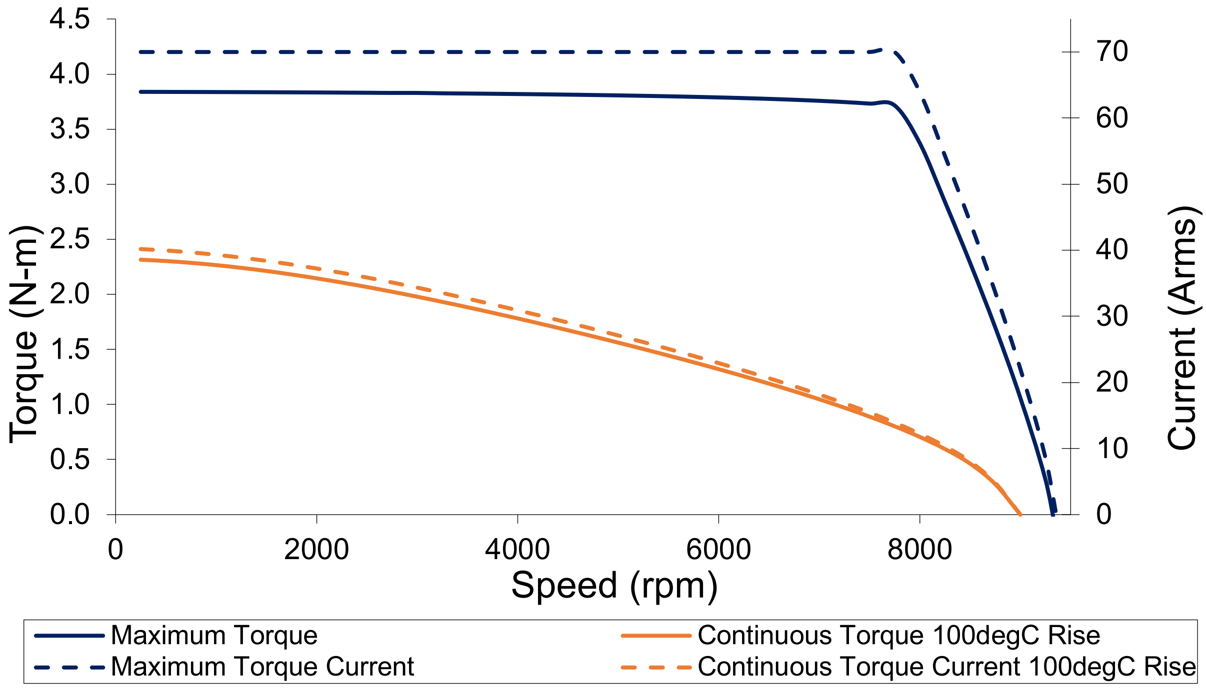

Figure 5-4: Torque/current-speed curve of generator (C3016-D) at 48 VDC

The PSM C3016-D is used as the generator due to the peak torque rating and the torque/current relationship at continuous and peak torque command. To operate the motor dynamometer system safely, the driving motor torque rating must be the same or lower than the generator torque rating. This way, both the driving motor and generator torque ratings are not exceeded. In addition, the PSM C3016-D torque-speed curve behaves differently at maximum torque compared to continuous torque before base speed. The PSM B3015-B torque-speed curve have a linear relationship for both continuous and maximum torque before base speed, which allows to calculate both torque and current accurately.

5.2.2 Motor Inverters (Motor Drives)

The motor and generator inverters support synchronous AC motors and are specifically for power steering motors. The motor inverters were donated at the same time with the PSM motors by InMotion US. Below are the main specifications of the advanced power steering (APS) controller. Note that motor and generator inverters are the same model number.

Table 5-2. Detailed motor drive specifications [42]

Motor Model Number	Specifications	
APS48M	Nominal voltage	48 V
	Operating voltage range	33 – 63 V
	Continuous RMS (1 hr.)	30 A
	Peak RMS (2 min.)	70 A
	CAN Communication	CANopen 125, 250, 400, 500, 800 & 1000 kbps
	I/O Connector	AMP SEAL 35-pin
	Operating temperature	-40°C to + 55°C
	Storage temperature	-40°C to +70°C

The motor and generator inverters are three-phase and are well matched for both the driving motor and the generator. Overall, the motor system is constraint by the driving motor. The driving motor nominal voltage is 48 VDC and maximum rated current is 30 A per Figure 5-3. Therefore, the maximum allowable motor power is 1.44 kW. As previously explained in section 4.2, the LV ESS design is largely driven to match the motor systems DC current and voltage requirements. The LV ESS nominal voltage is 52 VDC and maximum rated current is 30 A because of the BMS, refer to section 4.2.3. Thus the maximum allowable battery power is 1.56 kW.

Both inverters require a 35-AMP SEAL connector to power and control the motors. In addition, there are five power terminal connections to the motor inverters. Table 5-3 provides a description of the terminal connections.

Table 5-3: Motor inverter power terminal connections

Terminal	Description
B+	Battery positive termination (external battery fuse is required)
B-	Battery negative termination
U, V, W	Motor U, V, W -phase termination (3-phase)

Due to recommendation from InMotion, a heat sink is added to the component list for thermal dissipation. The heat sink must have at least one and a half times the surface area of the motor controller. The heat sink can be either flat or extruded aluminum surface. The surface area of the motor controller is approximately 26 in^2. Therefore, the chosen extruded aluminum heat sink is a 5.886 in. x 7 in. from HeatsinkUSA. Specific holes are drilled in the heat sink to match the mounting locations of the motor inverters.

5.2.3 Contactor and Pre-Charge Logic

To reduce the inrush current from charging the inverter capacitors, the motor inverter has a pre-charge system built-in. A main contactor is added to connect the DC bus to the motor inverter to drive the motors. The motor inverter has two power inputs, the B+ terminal and pin 3 (key switch) of the I/O inverter connector. The main goal of the contactor is to control the battery voltage to B+ by using the internal pre-charge circuit. To use the internal pre-charge, 52 V nominal is supplied to the key switch pin and the DC negative lead to B-. When the key is turned, power is supplied to the key switch of the motor inverters. The capacitors of both motor drives are charged. According to the APS3 manual, 10 seconds should be allotted to charge the capacitors. Once the capacitors are charged, the motor inverter signals the contactor to close. The contactor is controlled by the inverter using an open drain output to power the coil contactor. Specifications can be seen in the motor dynamometer schematics in Low Voltage Motor Dynamometer System Schematic.

The chosen contactor is a KILOVAC LEV100 Series 900 due to the high voltage rating and the reduced power consumption. The coil operating voltage is 12 V. The pickup voltage is 8 V with a dropout voltage of 1.2 V. The coil resistance is 26 **Ω**. The open drain output is set to 4 V to reduce the power consumption of the contactor to approximately 0.6 W. To control the contactor, the driving motor inverter is flashed with specific software to control the open drain output signals.

5.2.4 Dynamometer Coupler

Normally, a motor dynamometer has a torque sensor and couplings to fully couple the motor and the generator. Torque sensors prices average above $3000 in the market. Although torque sensors provide an accurate torque and speed reading, the prices are beyond the scope of this project. To accommodate these shortcomings, the DC supply for the motor and generator inverters are recorded to determine the efficiency of the overall dynamometer system.

To couple the generator and motor, a short section of Parker 7638 air conditioning hose is used. The Parker 7638 hose is high pressure and kink resistant. The hose inside diameter is smaller than the motor splines to provide enough pressure to follow the speed or torque command from the motors. The hose was tested prior the full design implementation and the generator was able to rotate the motor spline of the driving motor. Although this coupler is not an engineering solution, is a possible solution to complete the dynamometer setup. By using a high quality hose, it allows some deflection and provides some freedom for motor misalignment. The hose is 68 mm in length to reduce undesired vibration in the coupling system. Figure 5-5 and Figure 5-6 present a close-up picture of the dynamometer coupler and the motor spline.

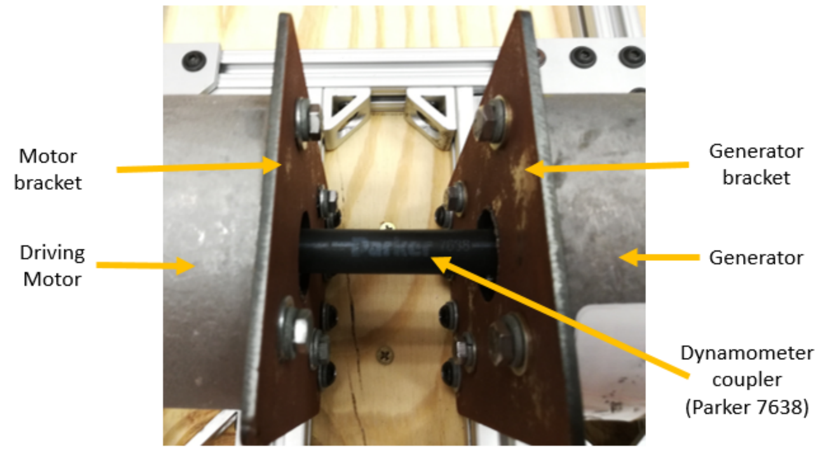

Figure 5-5: Dynamometer coupler integrated in motor systems

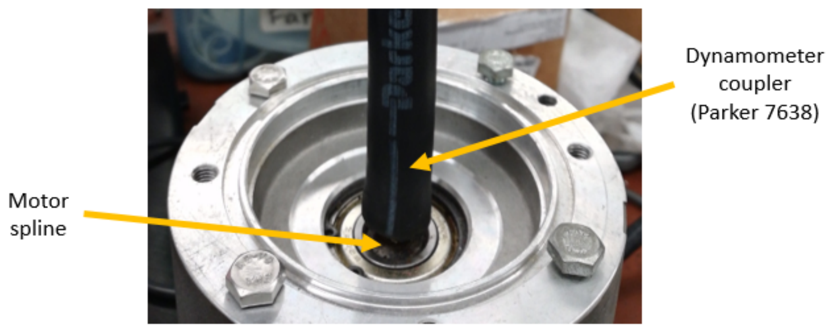

Figure 5-6: Motor spline and dynamometer coupler

5.2.5 Motor Mounting

To mount both the motor and the generator, a steel bracket is designed to resist the maximum allowable torque and weight from the motor. The generator motor torque is the worst case scenario for this system. Although the generator is never be used in torque mode, the bracket is designed in case the user tests the generator in torque mode. In addition, the generator weight is used as a requirement for bracket design. The bracket must tolerate a weight of 6.7 kg and 5 Nm of torque.

For ease, a rectangular bracket is designed with four lower holes to constrain the bracket to the bench test, and four holes equally spaced in a circle to mount the motor. The driving motor and generator have identical dimensions for mounting purposes, so the same bracket design is used. Note the driving motor has lower maximum torque rating compared to the generator.

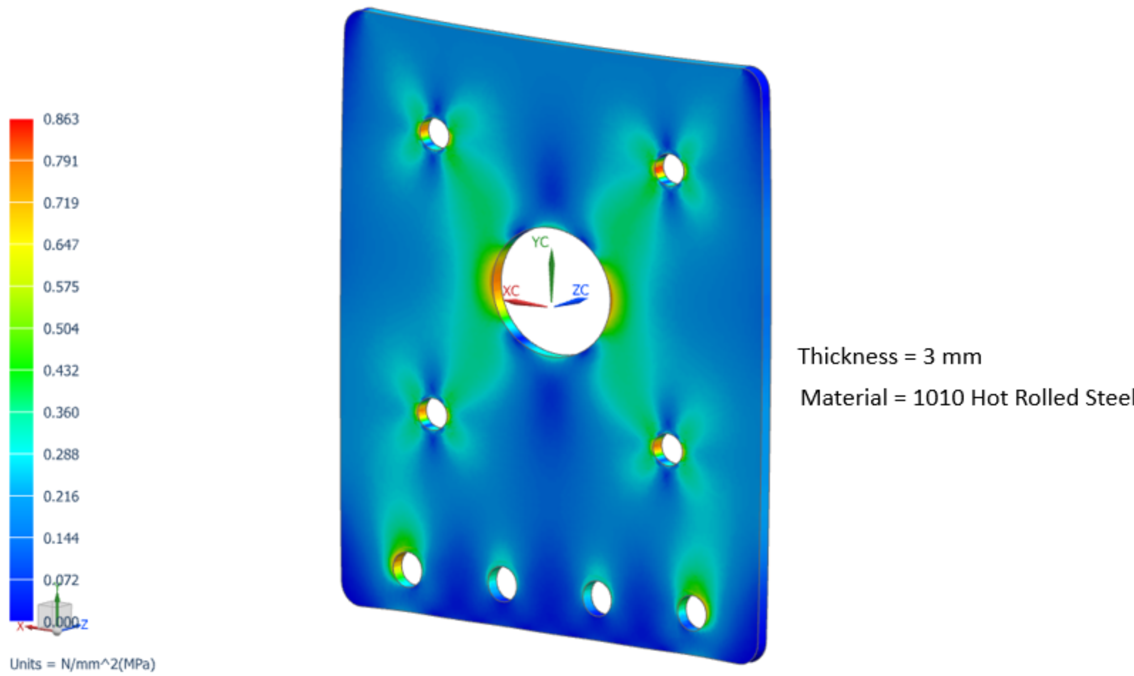

Figure 5-7: Stress analysis results for motor bracket at 5 Nm of torque.

Fixed constraints are used on the four lower holes. There are two load types: force and torque. The force corresponds to the weight of the motor and the torque is the maximum torque allowed using the InMotion data. 1010 Hot rolled steel has a yield strength of approximately 186 MPa and the results do not even reach 1 MPa of stress concentrations. This indicates the bracket is overdesigned. Most important is for students to understand loading and force reaction when designing a part.

5.3 Overall and Detailed Design of Motor Dynamometer System

The overall and finalized design is presented in Figure 5-8. There are specific components added in the final design for safety such as fuses, motor mounting base and a custom dynamometer torque coupling cover.

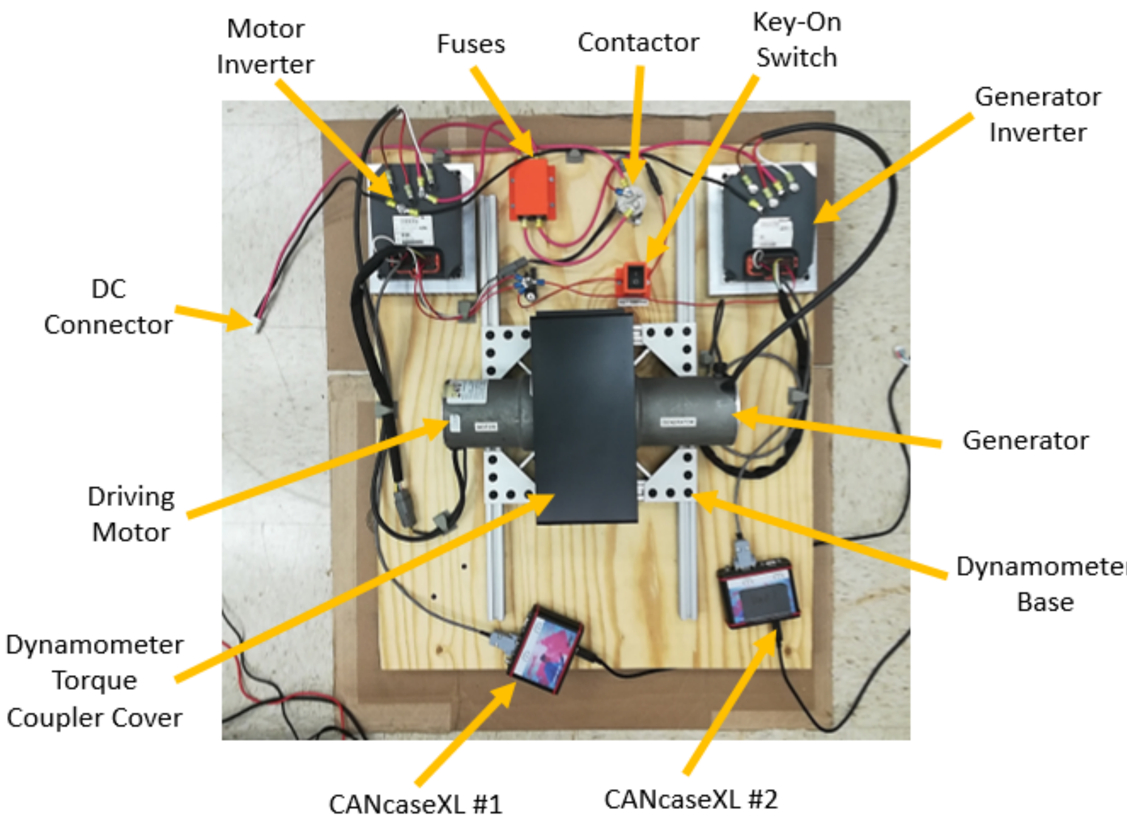

Figure 5-8: Final design product of motor dynamometer

A 72 VDC and 16 A rocker switch is selected to act as a key-on switch. The dynamometer torque coupler cover is a thin steel sheet cut and bent to fit the dimension of the dynamometer setup. Fuses are placed to protect the motor and generator inverter from an undesired current surge. Fuses are rated for 300 VDC and 30 A, slow blow. Two fuses are installed between the battery positive terminal and B+ terminals on each motor inverter. The fuses protect the motor controller and power distribution circuit in the event of a short circuit fault. During operation, the motor inverter depletes the LV ESS, so power flows into the motor inverter. Also, the generator inverter charges the LV ESS, so power flows out of the generator inverter. Section 5.5 explains in detail the power flow of the motor dynamometer.

5.4 Data Acquisition System

HEVT uses a main power analyzer as an instrumentation tool to test and record data for LV systems. This power analyzer is used as data acquisition for the motor dynamometer to teach students HEVT tools and software programs during the onboarding process.

The main tool used for data acquisition is the software Vector CANoe. The software is able to communicate with devices through CAN to read and send CAN messages. As a bidirectional communication software, CAN signals are monitored and recorded for further data analysis after testing. CAN signals recorded are presented in Table 5-4. The main controlled signals are denoted by the transmit designation (Tx) or receive designation (Rx), and operation details are explained in section 5.6 Motor Dynamometer Experimental Setup.

Table 5-4. CAN signals recorded from motor and generator

Application	Tx/Rx	CAN Signal	Unit	Description
Motor	Tx	Network Management (NMT)	N/A	Enable CAN Rx communication
	Tx	Open Drain Output 1	N/A	Digital signal to close contactor to power up inverters
	Tx	Enable Power Stage	N/A	Digital signal to enable the torque/current command
	Tx	AC Current Command	Arms	Commanded RMS motor current
	Tx	Torque Command	Nm	Commanded motor torque
	Rx	RMS Motor Current	Arms	Actual RMS motor current
	Rx	Actual Torque	Nm	Actual motor torque (estimated from inverter)
	Rx	DC Bus Current	Adc	Filtered DC bus current of motor inverter
	Rx	Filtered DC Voltage	Vdc	Filtered DC bus voltage of motor inverter
	Rx	Actual Speed	rpm	Actual shaft speed
	Rx	Motor Temperature	C	Temperature of motor
	Rx	Heatsink Temperature	C	Temperature of motor inverter
Generator	Tx	Network Management (NMT)	N/A	Enable CAN Rx communication
	Tx	Enable Power Stage	N/A	Digital signal to enable the speed command
	Tx	Speed Command	rpm	Commanded shaft speed of generator
	Rx	RMS Motor Current	Arms	Actual RMS generator current
	Rx	DC Bus Current	Adc	Filtered DC bus current of generator inverter
	Rx	Filtered DC Voltage	Vdc	Filtered DC bus voltage of generator inverter
	Rx	Actual Speed	rpm	Actual shaft speed
	Rx	Motor Temperature	C	Temperature of generator
	Rx	Heatsink Temperature	C	Temperature of generator inverter

The motor is operated in current mode instead of torque mode. The estimated torque from the motor inverter is very inaccurate, so RMS current is used instead to estimate torque. Figure 5-3, shows the torque/current-speed curve of the driving motor. Since the motor dynamometer is operated below 3000 rpm, the torque to RMS current relationship is linear. Thus, the torque to current relationship in the driving motor (B3015-B) is $0.10448\frac{Nm}{A}$.

The power analyzer is used to measure the DC bus voltage and current out of the power supply (LV ESS). Since estimated torque from the motor inverter is very inaccurate, the DC power in and out of a device is monitored to determine the efficiency of the system. More information about the operation procedure can be found in section 5.6 Motor Dynamometer Experimental Setup.

5.4.1 Computer Software Required

Several software programs are used to process data. These programs are used in industry and the goal is for incoming students to become experienced with these programs before students join HEVT for senior design. The only software that is InMotion proprietary is DriveTool. This is a custom software to monitor and program the motor inverters.

Table 5-5. Required software and purpose

Software	Purpose
CAD NX 10.0	Mechanical design of structure, wire routing, clearance between components.
MS Visio	Schematic design of components. Document all wire size and fuse size selected for the LV ESS.
MatLab	Math software analysis tool for data processing.
MS Excel	Math software analysis tool for data processing.
DriveTool	Inverter software creation. Introduce safety precautions such as voltage limits.
Vector CANoe	Software for motor control and data acquisition software.

5.5 Power Loss Model

To analyze the dynamometer system behavior, a power loss model is generated to determine the efficiency of the overall motor dynamometer system. Overall, the LV ESS powers up the whole system. Then the driving motor depletes the LV ESS by commanding AC current or torque clockwise (motor clockwise direction is out of the driving motor shaft). The generator commands negative speed because the 3-phase connection for both the driving motor and generator is the same. Thus, the driving motor rotational speed is clockwise into the driven motor shaft. The generator operates in the fourth quadrant and converts mechanical rotational power into electrical power to the DC bus. The dynamometer system experiences losses due to inverter losses, motor windings, shaft coupler, wire resistance and contactor. Figure 5-9 presents a diagram to generate the power loss model equations.

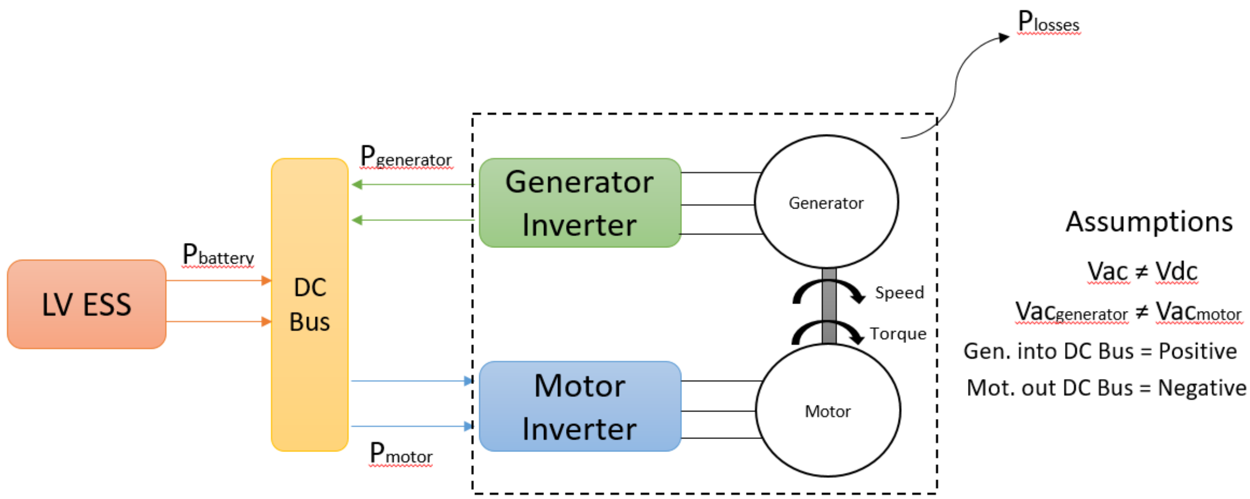

Figure 5-9: Power loss diagram model for motor dynamometer system

When power flows into the DC bus the sign convention is positive. When power flows out of the DC bus the sign convention is negative and the following power balance equation is generated.

$$P_{battery} = P_{motor} - P_{generator} + P_{losses} \tag{5}$$

Where $P_{battery}$ is the battery power coming out of the battery, P_{motor} is the driving motor power, $P_{generator}$ is the generator power going back into the DC bus, and P_{losses} is the power loss of the motor dynamometer system. Rearranging equation 5, the efficiency of the overall motor dynamometer system can be determined as the following:

$$\eta = \frac{P_{motor} - P_{generator}}{P_{battery}} \tag{6}$$

Note that the efficiency in equation 6 does not include any battery losses.

5.6 Motor Dynamometer Experimental Setup

To perform the dynamometer testing, all connections to the DC bus, inverters and motors need to be secured. To start the system, first the LV ESS must be connected to the DC connector. Then the MSD must be rotated 45 degrees clockwise to allow power discharge in the LV ESS. Then, instrument the LV ESS with the power analyzer. Use one hook voltage clip connector to monitor the pack voltage. An AC/DC current sensor is connected to the power analyzer to measure RMS current out of the LV ESS (remember to start recording prior testing). Figure 5-10 presents a diagram of the experimental setup.

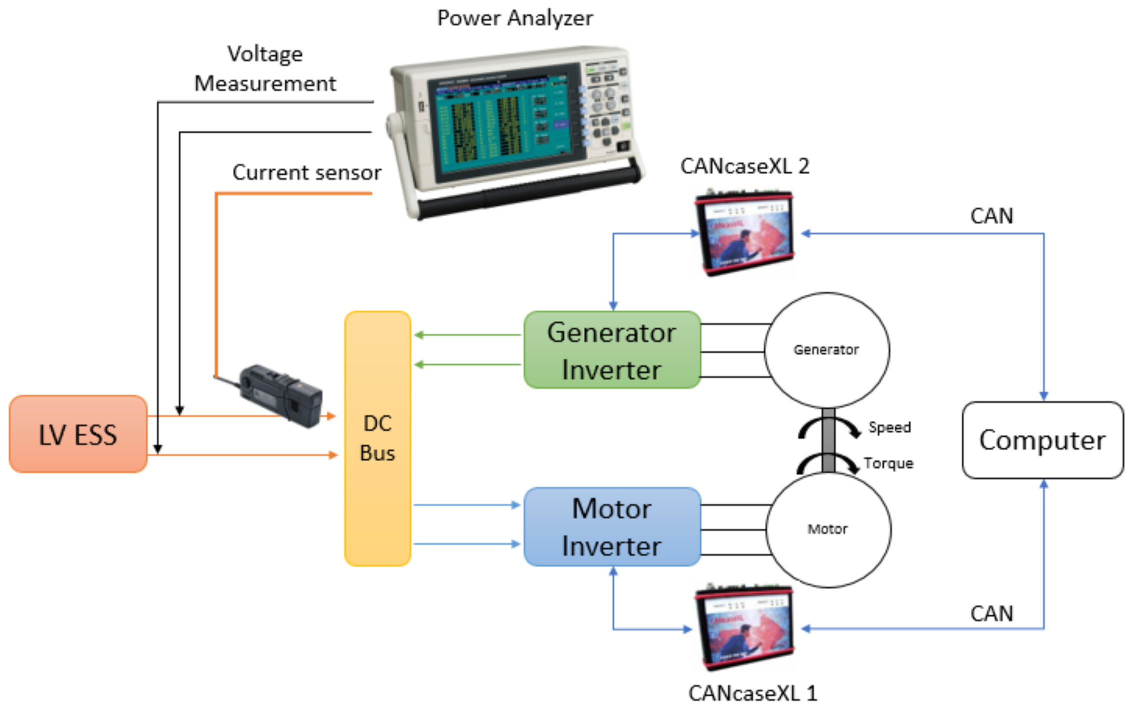

Figure 5-10: Data acquisition diagram for motor dynamometer system

The user must connect the CANcaseXL 1 and CANcaseXL 2 to the computer and load the configuration developed in Vector CANoe. Vector CANoe can be used to control both the driving motor and the generator inverters and monitor the CAN signals for data processing. In the Vector CANoe setup, 100 s/S (samples per second) are transmitted and recorded. The main control signals from Table 5-4 are used to power the motor and generator. The specific steps are as follows:

1. Vector CANoe software is open with the loaded configuration.
2. Turn the key-on switch to power up the internals of the motor and generator inverters.
3. Run program (configuration) to enable CAN communication between the control interface and the inverters.
4. Command a value of 1 for the NMT signal for the motor and generator inverters.
5. Allow 10 seconds for the inverter internal capacitors to be charged.
6. Command a value of 1 to the open drain signal to close contactor. Note the driving motor inverter has that specific signal, not the generator inverter.
7. Ensure the driving motor is in AC current mode and the generator is in speed mode. The driving motor is in AC current mode because the torque estimator on the motor inverter is inaccurate.

8. Enable power stage for the generator.
9. Command negative speed (i.e. 500 Rpm) from the generator to load the driving motor. Note a negative sign is used to ensure the driving motor stays in quadrant one and the generator stays in quadrant four.
10. Enable power stage for the driving motor.
11. Command an AC current from the driving motor. Start low (i.e. 1 Arms) and increase the value by one.

There are specific steps to follow when powering down safely the motor dynamometer. Mainly, the generator must always be commanding and rotating the shaft to prevent the driving motor from speeding up. The steps are as follows:

1. Command zero AC current from the driving motor. If AC current value is above 5 Arms, ramp down the AC current manually.
2. Turn off enable power stage for the driving motor.
3. Ramp down manually the generator speed to zero.
4. Turn off enable power stage for the generator.
5. Command a value of 0 to the open drain signal to open contactor. Note the driving motor inverter has that specific signal, not the generator inverter.
6. Stop the program to stop CAN communication between the control interface and the inverters.
7. Turn the key-on switch off.
8. Ensure no current is flowing in or out of the LV ESS and rotate MSD 45 degrees counterclockwise.
9. Finally, disconnect the DC connector between the LV ESS and motor dynamometer system.

5.6.1 Safety precautions

During the creation and implementation of the motor dynamometer system, safety considerations go into the custom software of motor and generator inverters. The main signal limitations are explained in the Table 5-6.

Table 5-6. Implemented limits on motor and generator inverters

Application	Signal Name	Value	Unit	Purpose
Motor	Open drain output mode	2	N/A	Enable the open drain output in voltage control to size requirements for contactor chosen
	Open drain output pull time	200	ms	Pull time for open drain output. Use contactor pull time.
	Open drain output pull voltage	8	VDC	Pick up voltage to close contactor
	Open drain output hold voltage	4	VDC	Hold voltage to maintain contactor closed
	Positive DC Current Limit	25	A	Positive DC current limit.
	Negative DC Current Limit	10	A	Negative DC current limit.
	Over speed forward limit	3500	rpm	Limits forward rotational speed of motor
	Over speed reverse limit	-3500	rpm	Limits reverse rotational speed of motor
	Moderately high level DC bus	58	VDC	Current starts to reduced linearly and a warning is set.
	High level DC bus	58.80	VDC	The inverter trips and power stops flowing to the motor.
	Moderately low level DC bus	45	VDC	Current starts to reduced linearly and a warning is set.
	Low level DC bus	42	VDC	The inverter trips and power stops flowing to the motor.
	Reduction end low level DC bus	42.50	VDC	Voltage is below this level, current is reduced to zero.
	Forward max AC current	35	Arms	Max acceleration of current in forward direction.
	Reverse max AC current	35	Arms	Max acceleration of current in reverse direction.
	Forward max brake current	35	Arms	Max braking current in forward direction
	Reverse max brake current	35	Arms	Max braking current in reverse direction
Generator	Positive DC Current Limit	25	A	Positive DC current limit.
	Negative DC Current Limit	10	A	Negative DC current limit.
	Over speed forward limit	4000	rpm	Limits forward rotational speed of motor
	Over speed reverse limit	-4000	rpm	Limits reverse rotational speed of motor
	Moderately high level DC bus	58	VDC	Current starts to reduced linearly and a warning is set.
	High level DC bus	58.80	VDC	The inverter trips and power stops flowing to the motor.
	Moderately low level DC bus	45	VDC	Current starts to reduced linearly and a warning is set.
	Low level DC bus	42	VDC	The inverter trips and power stops flowing to the motor.
	Reduction end low level DC bus	42.50	VDC	Voltage is below this level, current is reduced to zero.
	Forward max AC current	35	Arms	Max acceleration of current in forward direction.
	Reverse max AC current	35	Arms	Max acceleration of current in reverse direction.
	Forward max brake current	35	Arms	Max braking current in forward direction
	Reverse max brake current	35	Arms	Max braking current in reverse direction

The most important limits correspond to the DC bus and the rotational speed for both the motor and generator system. To protect the LV ESS, the inverters trip if DC voltage limit goes just below the peak voltage. The same occurs to the lower voltage limit at 42 VDC. This limit is chosen to not let lithium ion cells drop below 3 V per cell. As seen in the literature review section, the voltage of a lithium ion cell decreases exponentially once the cell is close to lower voltage limit. The driving motor rotational limit is lower compared to the generator. This is a chosen limit to not let the driving motor to over speed given it is set in current/torque mode. Note the driving motor can also be tested in regenerative mode. The motor current command must be negative to produce a counterclockwise torque and operate the driving motor in the second quadrant. Thus, the generator operates in the third quadrant.

6 Chapter – Results and Analysis

This chapter provides the results and discussion of both hands-on projects: the LV ESS and the motor system dynamometer. First the LV ESS results are discussed, where testing for both charge and discharge is performed. Second, results regarding the motor system dynamometer are presented. All results are generated using both MS Excel and MATLAB software.

6.1 Results and Discussion of LV ESS

As previously explained in the experimental setup, the LV ESS is loaded with high power resistors to discharge the pack at approximately 1C (i.e. 5 A). The battery terminal voltage and the current during discharge are presented next.

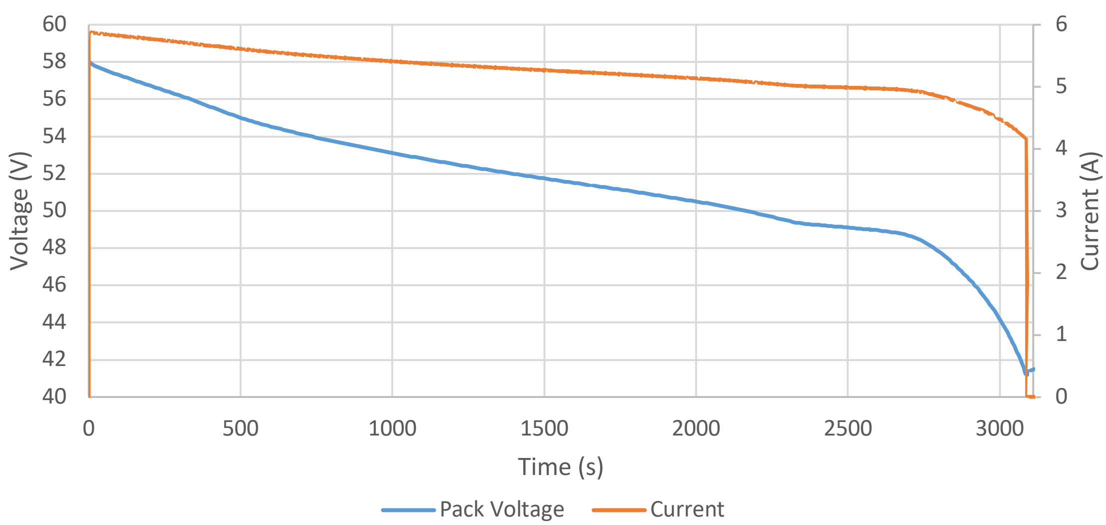

Figure 6-1: Battery terminal voltage and discharge current over time

The LV ESS voltage starts at approximately peak voltage before discharge. As voltage moves to the non-linear phase, the discharge current decreases non-linearly because the resistance of the load does not change. The average current discharge over the test is 5.25 A. Next the mid-cell and end-cell voltages are analyzed.

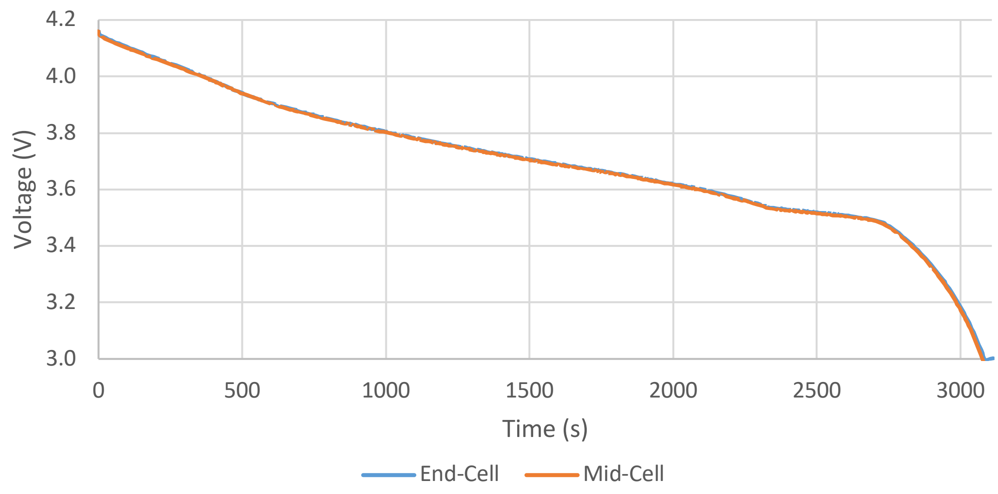

Figure 6-2: End-Cell and Mid-Cell terminal voltage discharge over time

There exist barely any differences between both lithium ion cells at this low discharge current. Figure 6-2 presents that both lithium ion cells have a similar capacity and are balanced. By the end of the discharge test, the difference between both cells is approximately 20 mV.

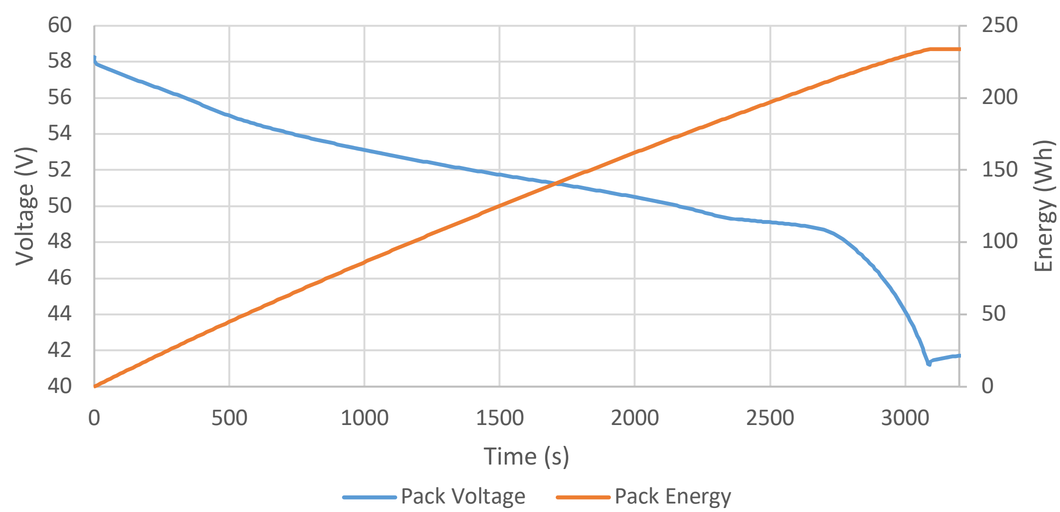

Figure 6-3: Battery terminal voltage and battery energy over time

During the discharge test, approximately 234 Wh of energy is depleted out of the battery. Using the nominal voltage of the battery pack, the battery capacity can be determined to be 4.5 Ah. The lithium ion cells are expected to have reduced capacity given these cells were cycle tested.

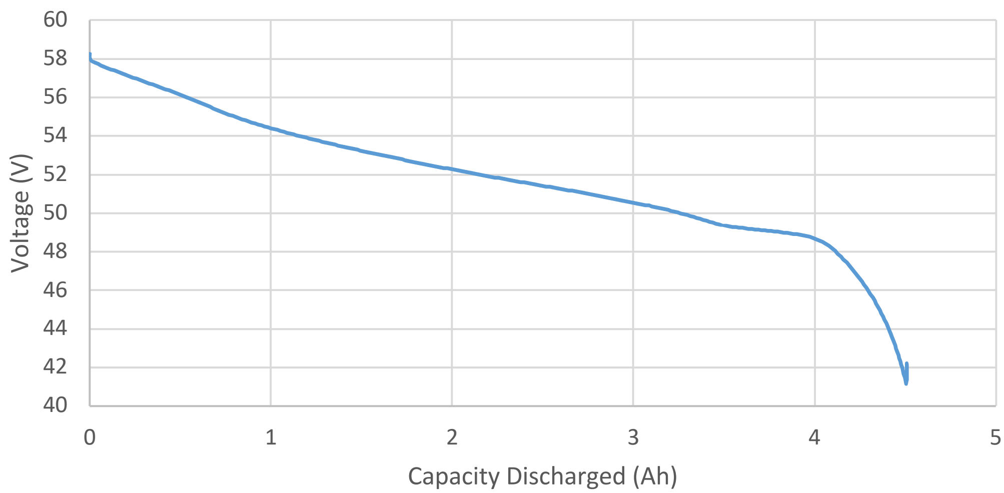

Figure 6-4: Battery terminal voltage over discharged capacity

Figure 6-4 reaffirms the calculated results from battery capacity. The temperature behavior of the mid cell is discussed next.

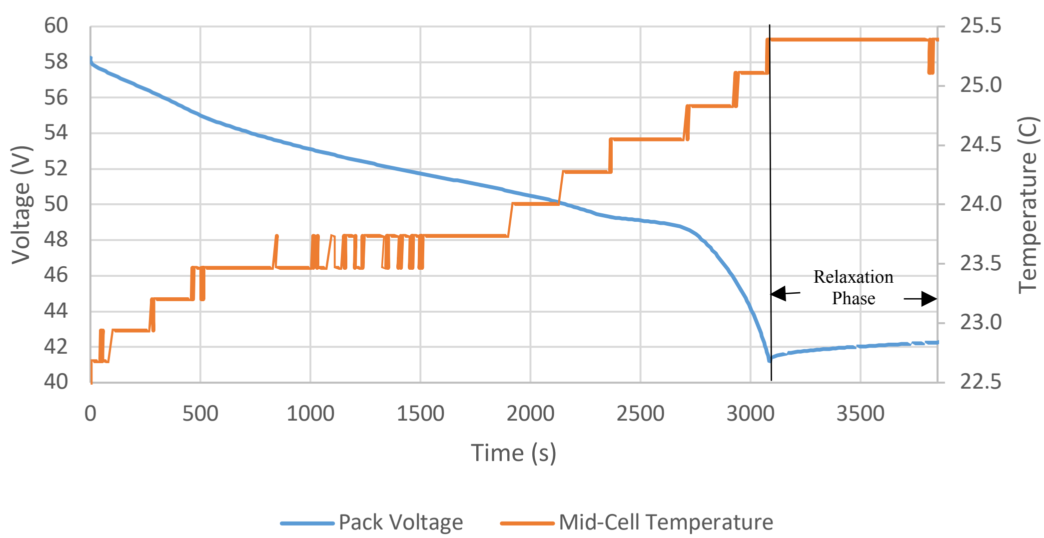

Figure 6-5: Battery terminal voltage and mid-cell temperature

The temperature of the mid-cell increases as the LV ESS is depleted. Note that the battery enters the relaxation phase when discharge current is zero just after 3000 seconds. During the relaxation phase, the mid-cell temperature stays constant. For a lumped thermal mass, it takes time to cool down. Next, the simplified battery model is used to calculate the internal resistance of the LV ESS.

Table 6-1: LV ESS internal resistance calculations

V_{oc} (V)	V_{Load} (V)	ΔV (V)	ΔI (A)	R_{int} (mΩ)	R_{int}/cell (mΩ)
58.34	58.02	0.31	5.88	53.24	3.80
56.71	56.41	0.30	5.72	53.17	3.80
54.80	54.51	0.29	5.52	52.88	3.78
53.60	53.31	0.28	5.40	52.82	3.77
52.61	52.33	0.28	5.29	53.66	3.83
51.76	51.48	0.28	5.20	53.61	3.83
50.62	50.35	0.27	5.09	53.49	3.82
49.49	49.23	0.27	4.97	53.55	3.83
46.56	46.31	0.25	4.66	54.07	3.86

A separated test is carried out to record the open circuit voltage and the voltage load of the LV ESS, refer to section 4.6. The time difference between V_{oc} and V_{Load} is 100 ms. The average calculated pack internal resistance is 53.4 mΩ, meaning each cell approximately has an internal resistance of 3.8 mΩ. Compared to the ANL battery testing, the averaged cell internal resistance is approximately 3.3 mΩ [48].

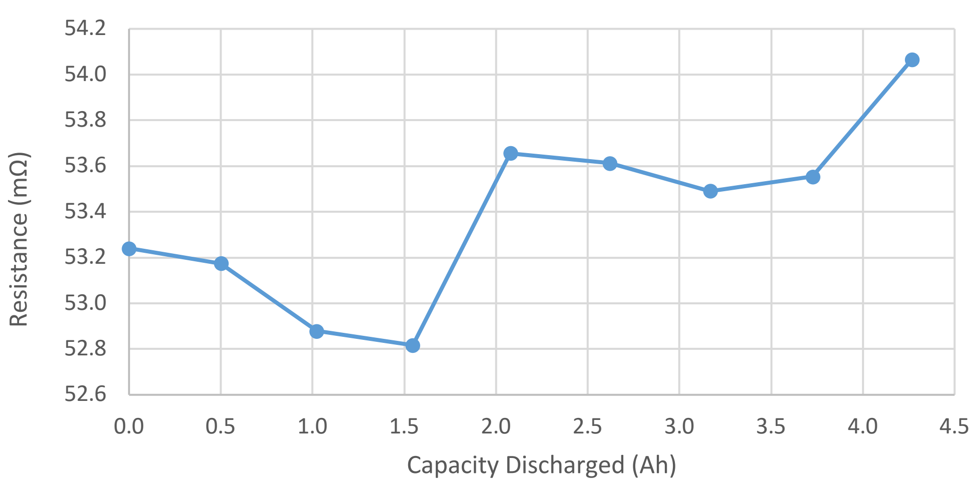

Figure 6-6: Calculated internal resistance over capacity discharged

Overall, the internal resistance seems to increase as the capacity is discharged. Study from Yang et al., shows that there is a relationship of OCV and internal resistance [28]. The internal resistance is high when the battery is fully charged or completely discharged. In this case, as the battery fully depletes, internal resistance increases to limit the current draw out of the battery. During the battery internal resistance test, the temperature of the mid-cell increased by 4°C.

As expected from the CC-CV charger, the charge current stays constant until the battery voltage reaches approximately 58 V. At that moment, current starts to decrease due to the CV phase of the charger. The averaged charge current over the charge test is 2.5 A (0.5C-rate).

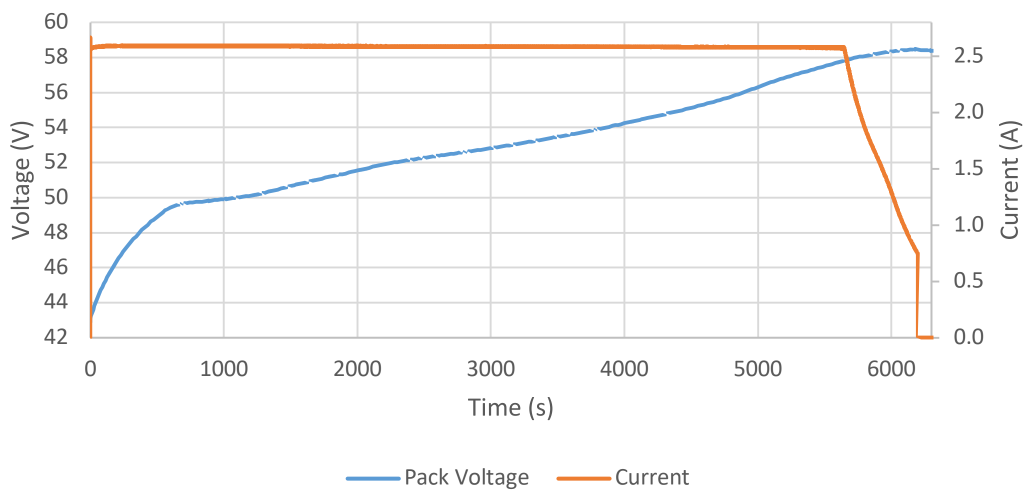

Figure 6-7: Battery terminal voltage and charge current over time

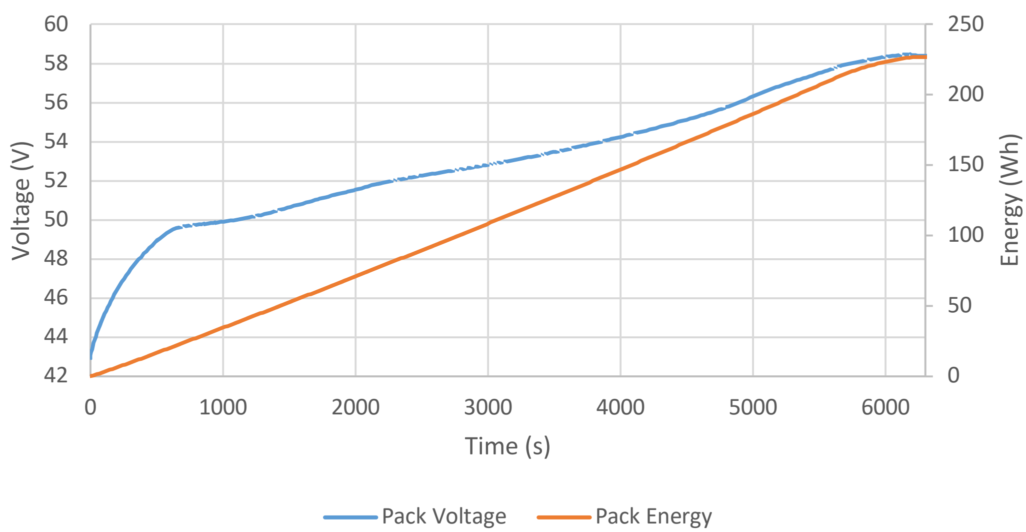

Figure 6-8: Battery terminal voltage and battery energy during charging

Approximately 227 Wh of energy is stored into the battery. Using the nominal voltage of the battery pack, the battery capacity can be determined to be 4.4 Ah.

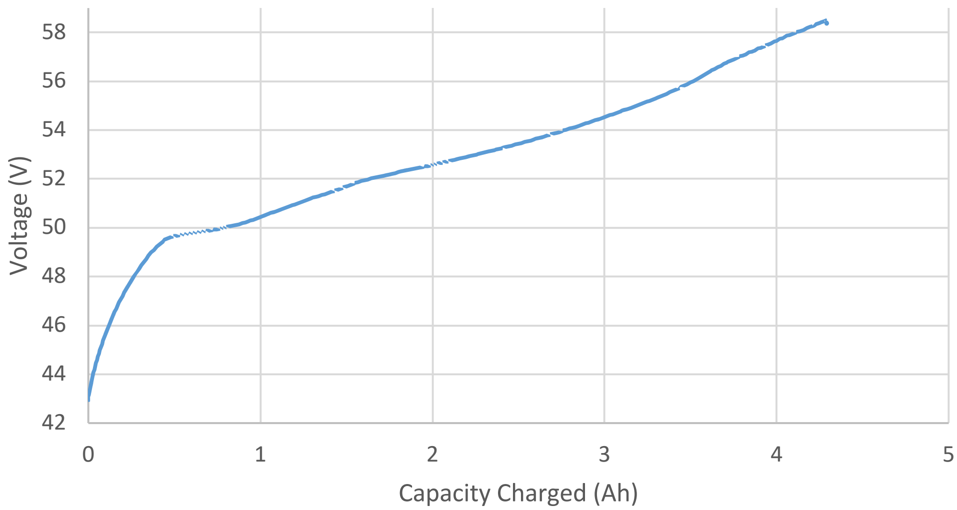

Figure 6-9: Battery terminal voltage over charged capacity

As seen in Figure 6-9, the capacity charged into the LV ESS is determined to be 4.4 Ah. This method also reaffirms the calculated battery capacity from the energy calculation in Figure 6-8. Next, the mid-cell temperature behavior is discussed during charging.

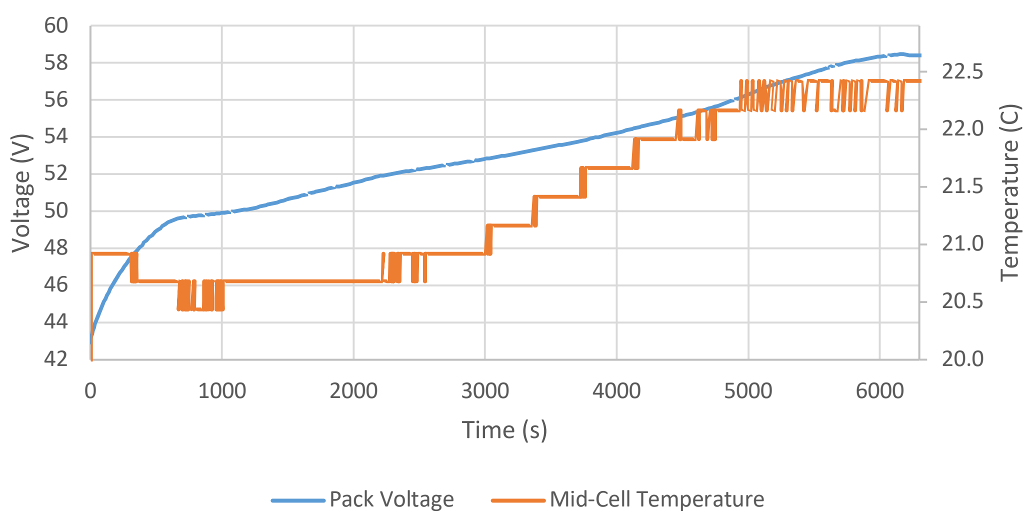

Figure 6-10: Battery terminal voltage and Mid-Cell temperature during charging

Prior charging the LV ESS, the pack was depleted and loaded with the power resistors. This allowed the pack to be heated prior to the charge test and the temperature started approximately at

21°C. Due to 0.5C charge rate, the lithium ion cells are not highly loaded and this allowed for the pack to stay cool for 30 minutes. The heating due to losses occurs in the core of the battery cell, and there is some time delay for the temperature response to reach the sensor on the surface. During both the charge and discharge test, the mid-cell temperature increased an average of 2.5°C.

6.2 Results and Discussion of Motor System Dynamometer

The motor dynamometer is tested by loading the system with the generator in speed mode and commanding AC current from the driving motor to generate torque. Both motors are tested below 3000 rpm to back calculate the torque command using the torque-speed curves from InMotion. The continuous torque case for the driving motor is used to create a torque to current ratio. The calculated torque to current ratio is $0.10448\frac{Nm}{A}$.

To measure the dynamometer efficiency, the generator loads the system every 250 rpm and the driving motor commands AC current from 1-5 A. Higher command currents affect the torque coupler design, therefore current results only discuss up to 5 A. To better visualize the plots, the loading case of 2000 rpm is chosen. Below are the plots of the LV ESS, driving motor system, and generator system.

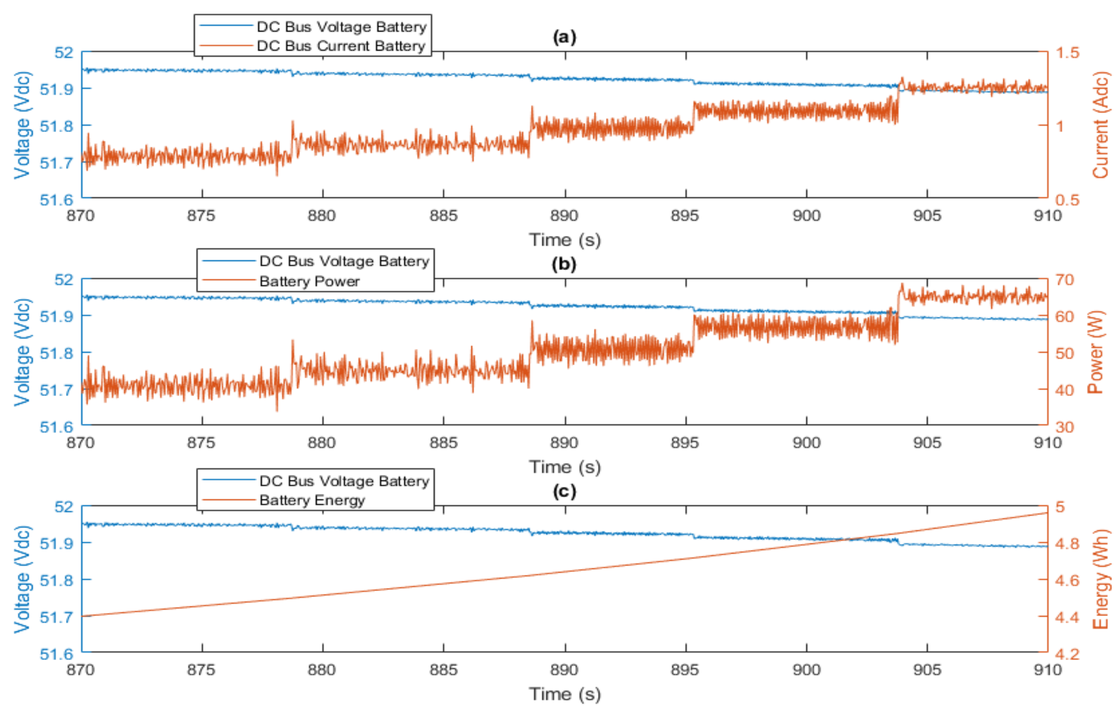

Figure 6-11: (a) DC bus current from the battery, (b) battery power, (c) battery energy

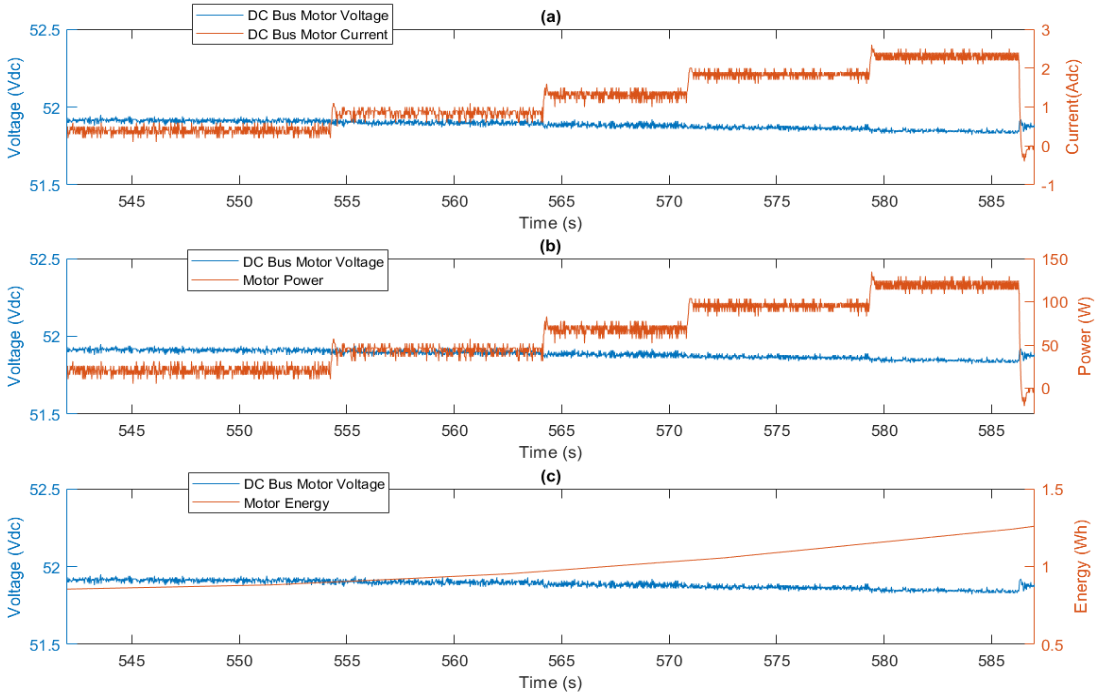

Figure 6-12: (a) DC bus current into the motor, (b) motor power consumed, (c) motor energy from driving motor

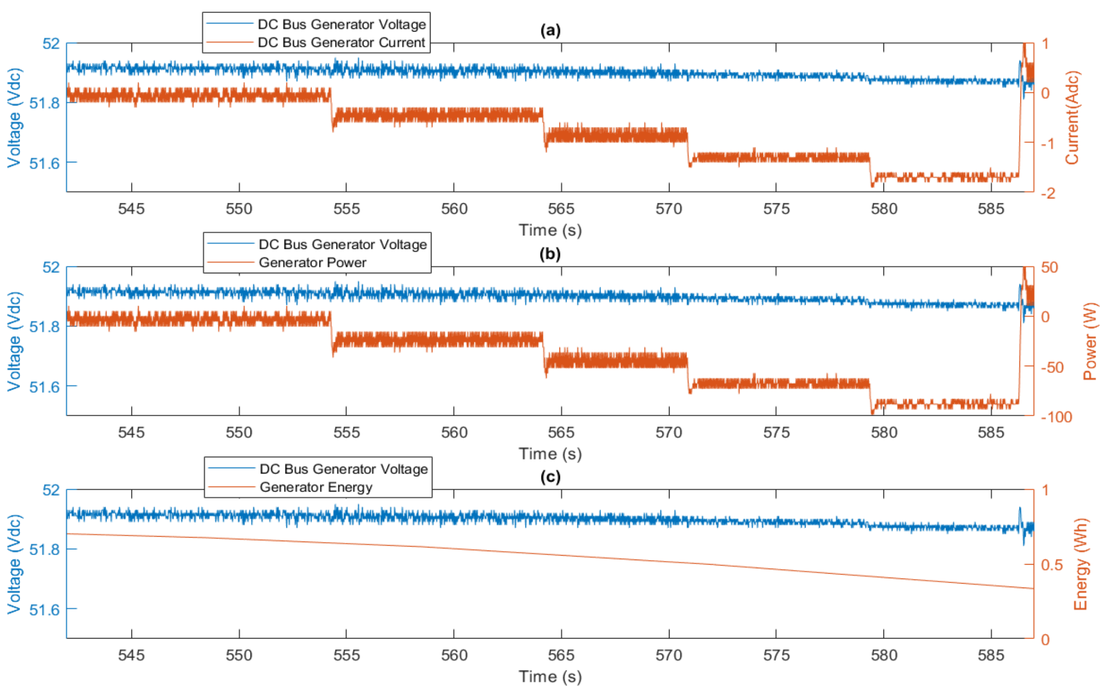

Figure 6-13: (a) DC bus current from generator, (b) generator power absorbed, (c) generator energy from generator

As previously explained in the experimental setup, the driving motor operates in the first quadrant to simulate a traction motor in a hybrid vehicle. The generator loads the system and operates in the fourth quadrant to generate electricity back into the DC bus. Note in Figure 6-12(b) the driving motor power is positive, while in Figure 6-13(b) the generator power is negative. The efficiency of the motor dynamometer is then determined.

Table 6-2: Motor dynamometer system efficiency

Expected Torque (Nm)	AC Current (Arms)							
0.52	5	52.3%	52.1%	56.1%	50.1%	47.9%	50.5%	47.7%
0.42	4	48.0%	50.3%	47.0%	47.0%	51.7%	46.2%	47.6%
0.31	3	39.3%	44.4%	44.8%	46.2%	47.1%	44.4%	43.2%
0.21	2	32.3%	39.3%	33.2%	36.7%	24.4%	40.4%	43.6%
0.10	1	48.2%	23.6%	25.7%	28.7%	40.9%	39.2%	42.4%
		500	750	1000	1250	1500	1750	2000
					Speed (rpm)			

Measurements at 1 Arms are very inefficient. At 500 rpm and 1500 rpm with 1 Arms, the efficiency provides false readings. The efficiency is higher than at 2 Arms. A possibility is the inaccuracy of the inverter readings at low power. In addition, the motor dynamometer system operates at an efficiency of approximately 50% at 5 Arms. The continuous current for the driving motor is 15 Arms. The dynamometer testing results are well below continuous current so it is expected for both motors to be somewhat inefficient. Losses are present due to contactor power draw and the voltage drop across wires, but mainly in the motor windings, inverters, and the coupler connection. The generator and the driving motors are different types, and the mechanical internals are unknown. Furthermore, the coupler connection is not a desired solution to the dynamometer system because the coupler connection can become undone with the motor and generator spline. This is a more likely scenario given the coupler connection is under cyclical loads. To test the safety limitations configured in the driving motor inverter, AC current is commanded on step until the inverter power trips due to the firmware limit set in Table 5-6.

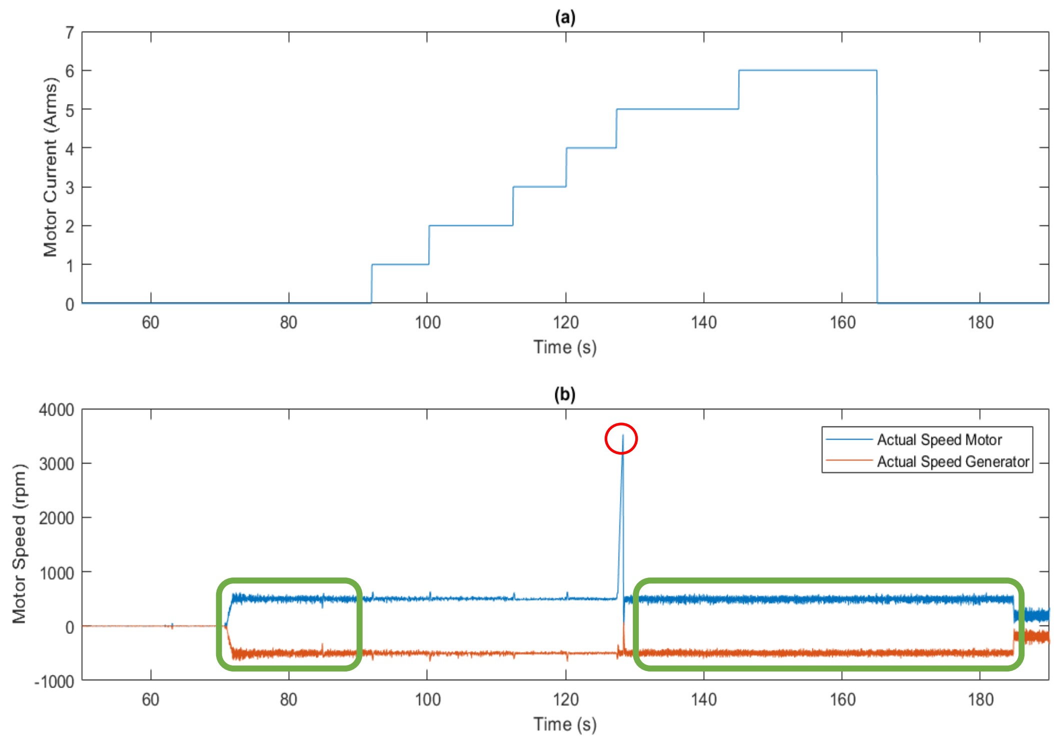

Figure 6-14: (a) AC current command from driving motor, and (b) motor speed comparison between driving motor and generator

Figure 6-14 (a) shows the AC current command. At approximately 130 seconds, the motor inverter tripped when the motor speed spiked (red circle). The speed spiked occurs because the coupler connection became undone and the driving motor speed up. Due to the rotation speed limitation implemented of 3500 rpm, the motor inverter trips. The driving motor stops to provide torque even though motor current command is not zero. The green boxes indicate when the driving motor is not providing torque. Finally, after the motor inverter trips, the generator still rotates the shaft until it is commanded otherwise.

7 Chapter – Summary and Recommendations

In summary, the onboarding process of HEVT requires new hands-on supplemental projects to improve the students' experience and improve knowledge transfer. The main goal is to implement two projects that complement each other to teach students the electric side of a hybrid vehicle. The hands-on projects incorporate a build activity that is missing from current HEVT projects. During the vehicle development process, teams fall behind because of ESS design, construction and commissioning. Likewise, controlling motor systems has been a difficult step that leaves teams behind schedule. The hands-on projects correspond to the design and testing of an LV ESS and LV motor system dynamometer. Students are required to use the LV ESS to power up an LV motor. The LV motor is mechanically coupled to another LV motor, acting as a generator. The generator is connected to the LV ESS to limit depletion and form a simple motor dynamometer. A simple battery model is used to determine the internal resistance of the LV ESS. This resistance is found to be 53.4 mΩ for the 14 cell pack. Also, the averaged discharge capacity is 4.5 Ah and the averaged charge capacity is 4.4 Ah. The motor dynamometer testing shows that the motor dynamometer system operates at higher efficiency when rotational speed and RMS current is increased. The efficiency of the motor dynamometer system at 5 Arms is approximately 50%.

Overall, both projects are demanding to build in one semester and will put incoming students outside their comfort zone. Team members exploring comfort levels will also be a healthy precursor when competing in AVTCs. Most importantly, both projects are built using low cost tools and reliable devices to ensure student laboratories can afford them. Finally, the hands-on projects are repeatable, therefore students have to design, build, test, and document all required work.

As for recommendations, two main components should be changed to improve the overall design of both the LV ESS and the motor dynamometer system: the BMS and motor coupling. Although the current BMS is reliable and monitors cell voltage, a CAN controlled BMS will provide additional capabilities to control the LV ESS. CAN controlled battery management systems have the capability of thermal management systems, which can simplify external wiring. A second recommendation is to fuse all BMS balancing wires for safety to reduce the chance of a short. Finally, the mechanical coupler needs to be improved to provide a more secure and robust coupling between the motor and generator. By improving the coupling, motor dynamometer testing could be performed at higher power demand. A separate project to create a custom spline coupler would be useful to be presented as an external project in the onboarding process to compliment the motor dynamometer system project.

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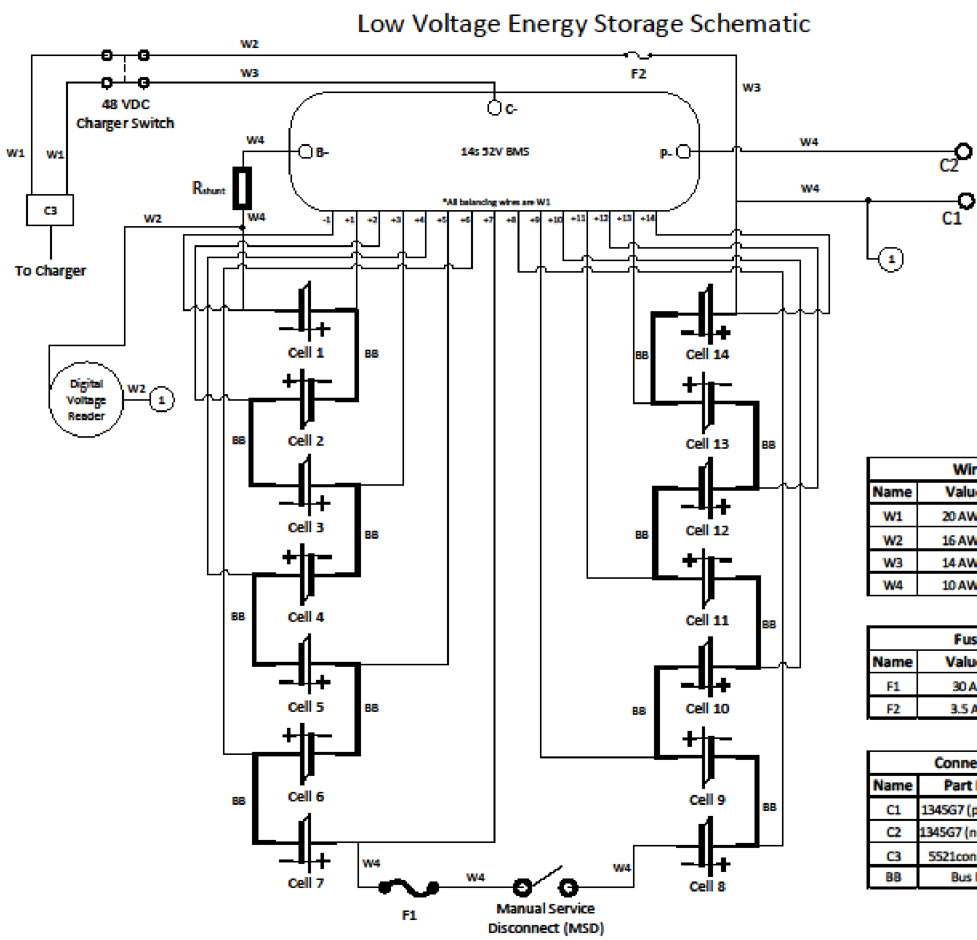
Appendix A: Wiring Schematics

Low Voltage Energy Storage System Schematics



Wire Information

Name	Value	Part No.
W1	20 AWG	WM 20 Waytek
W2	16 AWG	WM 16 Waytek
W3	14 AWG	WM 14 Waytek
W4	10 AWG	6659T14 McMaster

Fuse Information

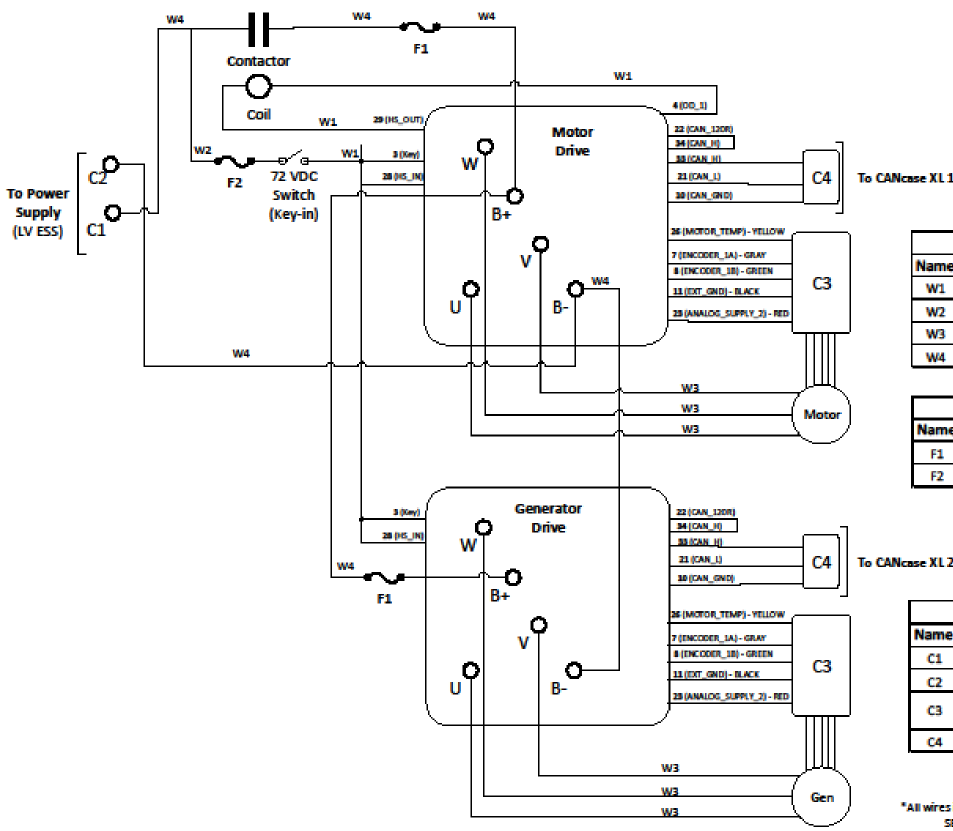
Name	Value	Part No.
F1	30 A	Littlefuse 0HEV030.ZXC
F2	3.5 A	Littlefuse 022503.5HXP

Connector Information

Name	Part No.	Manufacturer
C1	1345G7 (positive)	Anderson Power Products
C2	1345G7 (negative)	
C3	5521connector	Vruzend
BB	Bus Bar	Stock

Low Voltage Motor Dynamometer System Schematic

Low Voltage Motor Dynamometer System Schematic



Wire Information		
Name	Value	Part No.
W1	18 AWG	WM 18 Waytek
W2	16 AWG	WM 16 Waytek
W3	12 AWG	Stock
W4	10 AWG	6659T14 McMaster

Fuse Information		
Name	Value	Part No.
F1	30 A	Littlefuse 0HEV030.ZXC
F2	10 A	Littlefuse 0225010.HXP

Connector Information		
Name	Part No.	Manufacturer
C1	1345G7 (positive)	Anderson Power Products
C2	1345G7 (negative)	
C3	DTM04-6P (male) DTM06-6S (female)	Deutsch
C4	C&P 9F	L-com

*All wires into and out of the motor drives 35 AMP SEAL connector are 18 AWG (W1)

Appendix B: Pairwise Comparison Chart template

Subteam						
Normalized Weight	**Requirements**	**Design #1**	**Design #2**	**Weighted 2**	**Design #3**	**Weighted 3**
8.00%	Reliability					
12.00%	Serviceability					
4.00%	Noise/Vibrations					
20.00%	Safety					
4.00%	Lightweight					
4.00%	Aesthetic Appeal					
8.00%	Manufacturing					
8.00%	Component test structure					
8.00%	Cost					
12.00%	User interface					
12.00%	Controller interface					
	Total					