NAU NORTHERN ARIZONA UNIVERSITY
School of Informatics, Computing, and Cyber Systems

The Baja Brothers

eBaja Final Report and User Manual

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Introduction

Client Background:

The eBaja team wanted to provide our client, Dr. Venkata Yaramasu, with an electric-powered vehicle capable of competing in an off-road competition while maintaining all industry-wide safety standards. Dr. Venkata Yaramasu is a professor at Northern Arizona University and specializes in electric drive technologies and power electronics. Currently, Dr. Yaramasu is involved with the Salt River Project to analyze the impact of zero net energy homes in Arizona and the development of charging stations for electric vehicles. He teaches various subjects here at NAU such as wind turbine technologies, electric drives, and an electric vehicle class. He also sponsors the electric vehicle club here at NAU and took lead on this year's capstone project to expand the club and give the students more motivation. The completion of this project will provide the students with more insight into what the club can evolve into over the next few years as well as the impact it will have on the school and environment. The eBaja team is honored to have worked with Dr. Yaramasu over the last year and the knowledge gained from this project.

Problem Statement:

The objective of this project was to convert a mechanical Baja vehicle into an electrical vehicle by combining the skills and knowledge of 9 students, composed of 5 mechanical and 4 electrical engineers. At the end of this project, we will be competing in a Baja vehicle competition down in Phoenix which will be the basis for our requirements. We will be representing NAU as the first electric vehicle designed and built by a group of students. This was accomplished by mounting a custom-made battery to the vehicle and testing its capabilities to determine its strength and endurance. As electrical engineers, we specialized in replacing the gas engine with a battery pack, an electric motor, and a controller. The battery-powered a Permanent Magnet Synchronous Motor to propel the vehicle, so our team designed a load test to find the limits of the battery. The results of these tests enabled precision adjustments to the system to protect the battery and vehicle. Our client is Venkata Yaramasu who is a professor here at Northern Arizona University. He worked closely with the E-Baja capstone group in 2019 and has taken the same role with us this year. This vehicle will eventually be used in future SAE Baja Competitions making it pivotal to create a working prototype by the end of the year.

Design Process

Description:

To design a powerful, fast, and reliable vehicle that runs exclusively on electric power, the team began the design process by finding the strengths of each of our team members. We assigned roles and responsibilities to each member based on a voting system we implemented. The team then developed a system architecture of our system using research we conducted on the project and the resources we were given. From there we needed to implement the requirements given to us by our client by breaking up our system architecture into four components. Each member took on the challenge of creating a prototype to determine the individual functional blocks of our system. The team divided the system into a second custom-made battery, the auxiliary system, the plug design, and the user interface. The Battery Prototype Can be found in Appendix A. Each member was to apply their learning methods to research and design a prototype to be used on the vehicle. These prototype findings shaped our project design and the steps the team needed to take to complete the vehicle. Developing these prototypes early on in the design process gives the team opportunities to test and improve these designs. Finally, the team also had other components aside from the four major ones that are outlined in the functional decomposition below. We needed to implement kill switches on both the inside and outside of the vehicle for safety purposes. Additionally, we needed to come up with a vehicle design that contained proper insulation of the wires and mounting brackets for our components. This design process took multiple weeks to gather a good outline to begin the construction phase.

Functional Decomposition:

Figure 1 shows levels 0 and 1 of the functional decomposition of the eBaja system. For level 0, the inputs and outputs are specified. Most of these inputs tie to the motor controller as can be seen in level 0, however the lights toggle relates to the auxiliary lights. This toggle represents the multiple switches used to control the headlights, taillights, and turn signals on the vehicle. The other inputs are the two planned kill switches. These will cut power to the system when flipped. The outputs to the system are the motor speed, which is controlled by the throttle, and the motor direction which is controlled by the drive mode switch. The final output are the lights, which are controlled by the various light toggles.

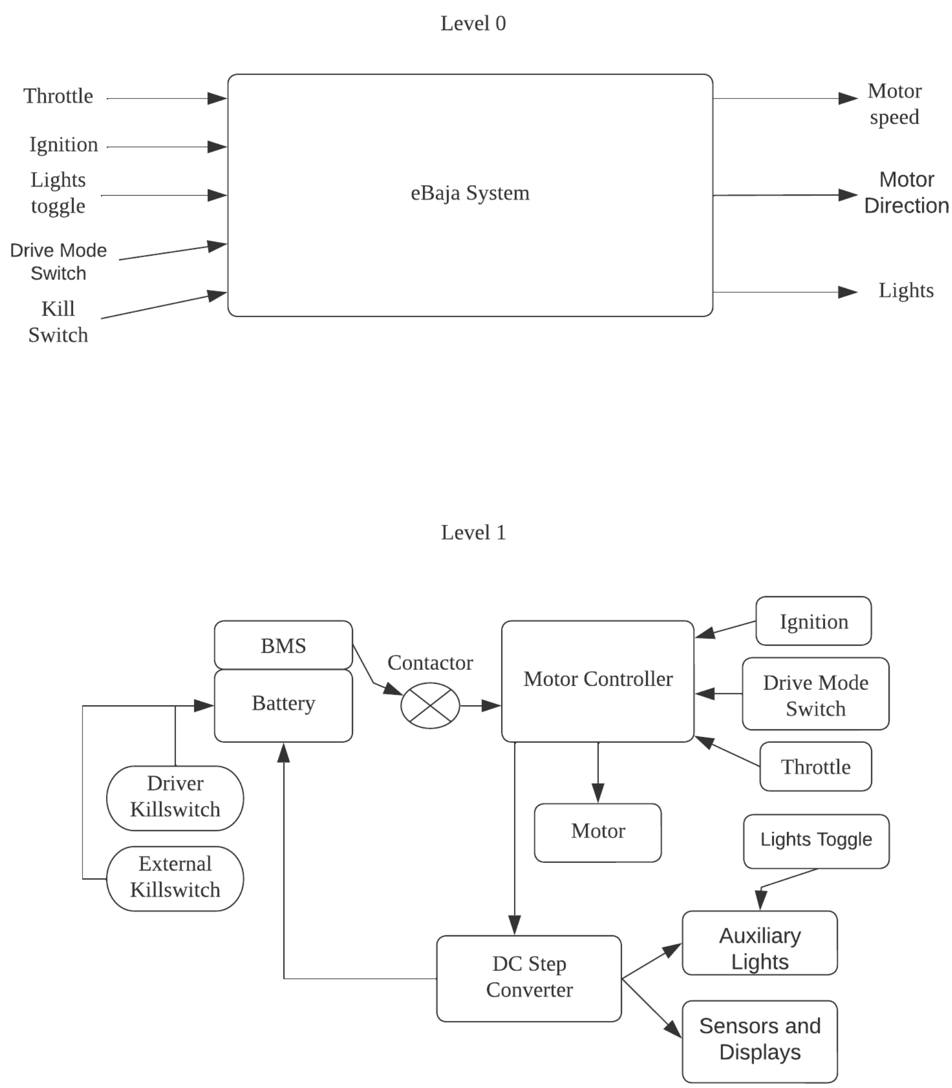


Figure 1 - eBaja functional decomposition

Prototype Findings:

Plug Prototype:

With how close the terminals are on the battery pack, making a more permanent connection at the battery terminals and making a plug connection further away from the pack is necessary for safety and ease of battery swapping. The team was working with 4/0 gauge power cables to deliver power to the rest of the electrical system. After an unloaded test of the motor, the team predicted under load the amperage pulled by the motor controller would be about ten times the amount of amperage being pulled unloaded. Seeing as 6A was seen being pulled by the motor controller, it is predicted a load amperage of close to 100A could be seen when operating on the vehicle. Knowing that the more current a wire will have to cross over it, the more width a wire needs, it was theorized that four 12-gauge wires would distribute the current evenly and safely.

However, manufacturing this prototype had some issues. First, the plug used were simple 12-gauge c-clamps with plugs on one side and sockets on the other. This made disconnecting the “plug” easy, but manually plugging in four separate strands took time, not to mention the fact that these clamps would loosen through use and were not very secure. The second and larger issue was the incorrect assumption that these wires would evenly distribute the current running through them. Electricity flows through the easiest path, and so with no resistive elements in each wire, the flow of electricity would most likely only go through one wire, defeating the purpose of the other wires and “distributing” the current.

Alternatively, available for purchase were large gauge plugs that could fit up to the 4/0 cables the system was using. This would be a better replacement for the aforementioned plug prototype as they not only could fit the cables, but they also have a strong connection force that requires more force to disconnect. This makes the plug connection much more secure for the application of an offroad vehicle and will be more resilient to the physical stresses placed on the system. With the plug having a stronger connection force, the shaking and rocking of the vehicle should not disconnect the plug from the rest of the system and shut down the vehicle.

Unfortunately, the team was unable to install the plug onto the final version of the system. Two plug sizes were ordered just in case, as the team originally wanted to step the cable gauge down to 1/0 size cables due to the assumption the battery would only reach 100 Amps. However, during testing, the battery exceeded 130 Amps meaning the amperage capacity would have been exceeded on 1/0 cables. Currently, the system still uses 4/0 gauge cables, but 2/0 could potentially be used as that capacity is up to 150 A. This is a possible size to reduce the weight of the cables that weigh down on the battery terminal connections and would make the cables easier to mount to the vehicle.

Auxiliary System Prototype:

The Auxiliary System prototype draws power from the vehicle battery to power various peripheral components. These include brake lights, headlights, tail lights, turn signals, and indicator lights on the sensor display. The components are all rated for 12 Volts or less, so to power the Auxiliary system we used a 12V DC/DC step-down converter provided by the client to utilize the proper voltage for the circuit.

The most significant challenge was a voltage control issue for the turn signals. Because we used a special logic chip with capacitors to discharge the turn signal lights with the blinker circuit, the voltage supplied to the turn signals hit a soft wall and the LEDs did not produce enough brightness to be visible. To resolve this, we rerouted the blinker circuit to transistors to open and close the gates and allow electricity directly from the source to power the LEDs instead, which produced a satisfactory brightness. The prototype we designed and built-in lieu of the actual vehicle lights was a miniature proof of concept circuit built on a breadboard and fit inside of a standard shoebox. It included switches for all of the light systems and ran on a 5V power supply to represent the battery, using small LEDs. To represent the sensor display there are separate LEDs in the corner of the prototype.

User Interface Prototype:

The last prototype consisted of designing and implementing sensors into our system to read and analyze data while operating the vehicle. We chose to prototype this subsystem as the ability to track the voltage and current of the battery is of utmost importance. The competition we are competing in has a speed limit of 25 MPH which makes it imperative to have a visible speedometer for the driver as well.

Early on we researched a speedometer and found conventional speedometers were not compatible with our system. We found a wired sensor that connects to the wheel and reads rpm's, but unfortunately with our vehicle competing on rough terrain this turned out to not be feasible. With the sensor mounted to the wheel, off-roading may send dirt and debris toward the sensor causing an increase in error percentage or even system failure. Our prototype reduces the risk of the entire project tremendously, providing the driver with the speed of the vehicle, which will reduce the driver from breaking rules in the off-road competition. Being able to monitor the voltage will allow the driver to detect when the battery reaches a dangerous level and needs to be charged or replaced.

We were able to successfully demonstrate the state of charge sensor by running the positive terminal wire through a hole that reads the current flowing through it. When we applied the throttle, the current fluctuating based on the rpm was visible. We did run into some challenges along the way but in the end, we were able to get the results we expected. We were able to calibrate the sensor to our Battery Management System to guarantee a small percentage of error. Unfortunately, the RPM sensor was not able to convert to MPH in our final design so we only had an RPM reading. In future projects, the goal would be to have an Arduino or MCU to convert the RPM to MPH in real-time.

Final Design

System Architecture:

Figure 2 outlines the overall system architecture of the team's electric vehicle. Our system starts with the custom-made 20-cell battery pack that runs off 80V of electricity. Cell data is then passed through the positive terminal of the battery to the battery management system located at the top of the battery. This system manages each of the 20 cells individually to ensure cell balancing over the entire battery pack so no cells are overcharged or undercharged. From there the vehicle contains an auxiliary system containing the headlights, brake lights, and turn signals powered by a 12V step-down converter. Multiple sensors and toggle switches are located in the user interface at the front of the cockpit.

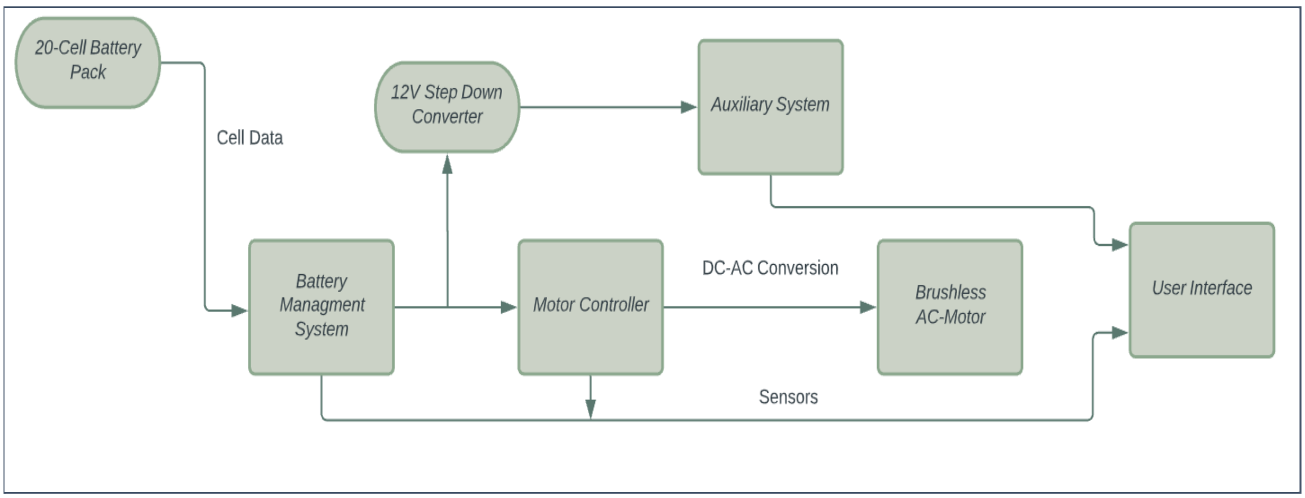


Figure 2 - Overall system architecture

Figure 3 is an outline of the behavior of the auxiliary system. It shows how each of the components turn on and off depending on if the system is currently on and the position of switches.

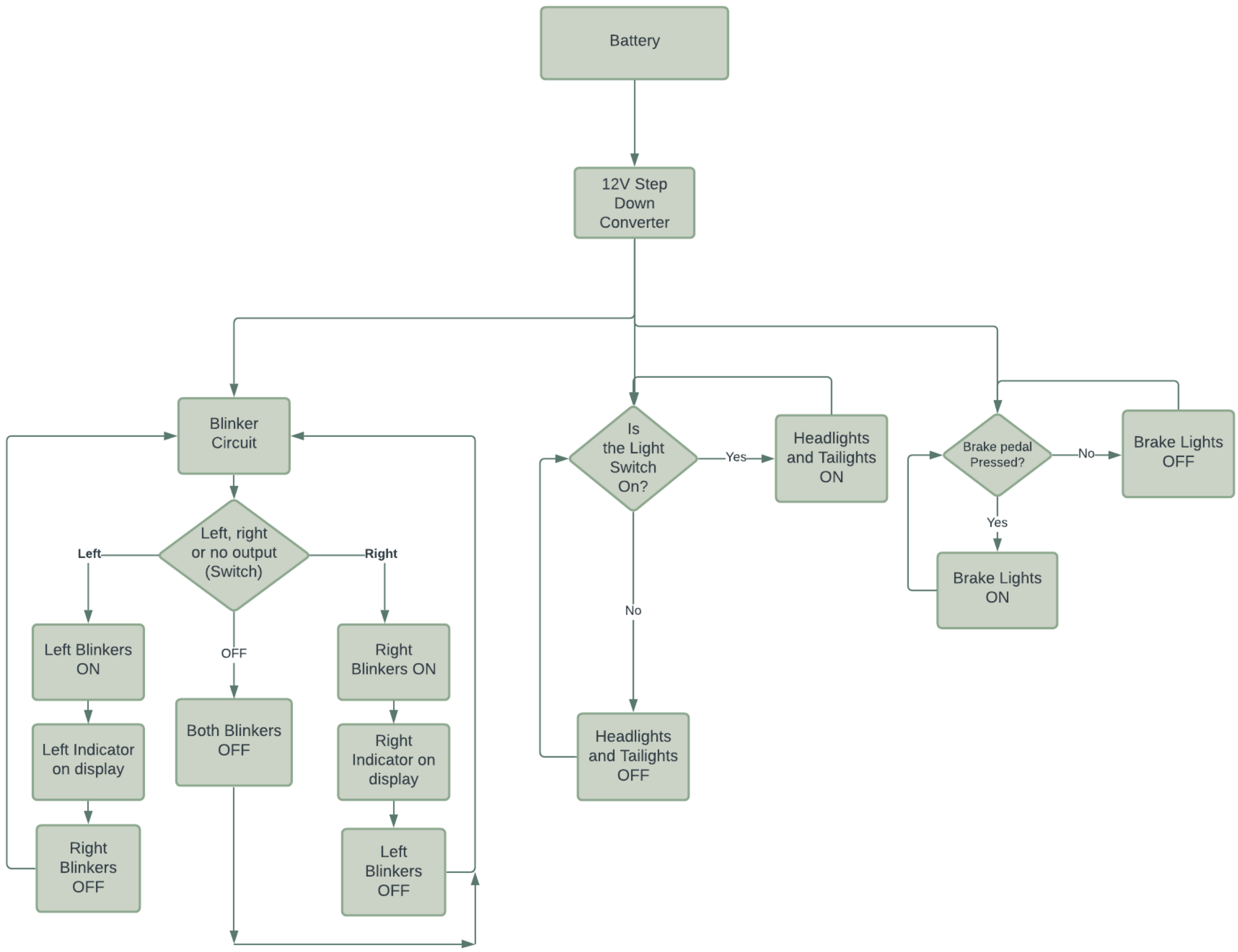


Figure 3 - Auxiliary Level 2 Design

Figure 4 below outlines the user interface and the two sensors we used to track data during operation. On the left side of the picture, there is a speedometer and state of charge sensor. The speedometer sits in the cockpit of the vehicle and gathers the RPMs of our motor. This information is then converted into MPH so the driver knows how fast the vehicle is moving. We then have a few LEDs in the cockpit that show the lights or turn signals are on, all of which can be manipulated using buttons or switches.

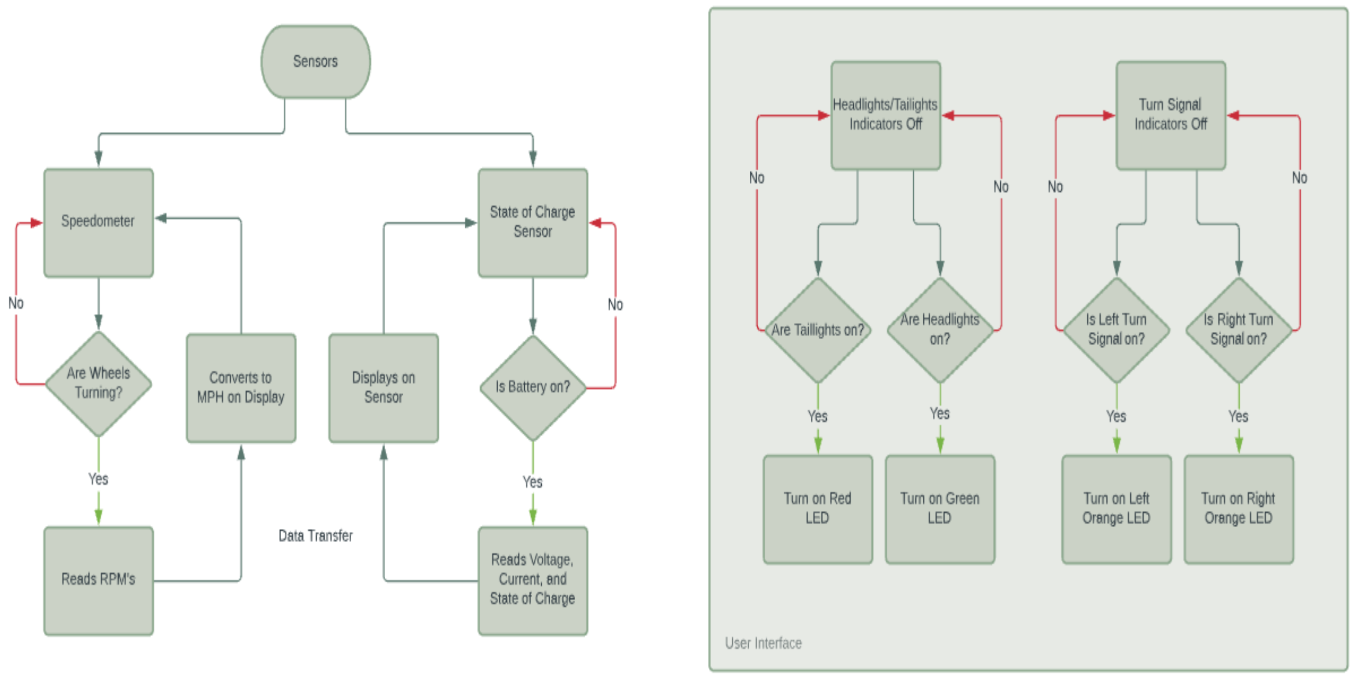


Figure 4 - User Interface/Sensors Level 2 Design

Results

Figure 5 outlines the requirements of the system and the respective test results shown by the color. Green indicates the test passed, yellow indicates the test could not be finished due to design issues or integration failures, and red means the test failed. Many of these tests were done using the load testing platform shown in Appendix A.

Type of Te	Status	Req #	Requirement
		1	**Battery**
UTM		1.1	The battery will power the buggy system for at least 20 minutes at 50% throttle
UTS		1.2	A second identical battery will be constructed for ease of battery switching during the competition
UTS		1.3	Both batteries will have plug attachments to the system for quick plugging and unplugging from the vehicle.
Inspect		1.4	Battery management system for cell safety and voltage regulation.
UTM		1.5	Batteries current will not exceed 130A per battery specifications
UTM		1.6	Load test to verify batteries current state
UTM		1.7	Battery will be rated to run at 65A for 1 hour
		2	**System**
		2.1	Auxiliary
UTS		2.1.1	Tail lights will be present for safety
UTS		2.1.2	Headlights will be present
UTS		2.1.3	Turn signals will be present
Inspect		2.1.4	Auxiliary lights will be supplied by 12V via DC-DC step converter
UTS		2.1.5	High/Low beam lights will be present
		2.2	**Kill switches**
Integration		2.2.1	Switch inside the cabin for the driver to reach in case of emergency.
Integration		2.2.2.	Identical switch outside the cabin for bystanders in case of driver incapacitation.
UTM		2.2.3	Both switches will be rated for 80V
		3	**Safety**
Integration		3.2	Battery terminals and conductive components will be insulated.
Integration		3.3	Electronic mounts and straps to ensure components are stable during a crash
Integration		3.3.1	Components will have no disconnections when experiencing rough terrain
Inspect		3.4	Safe placement of electrical components behind the chassis
Inspect		3.5	Motor controller will contain a heat sink (thermal fins) for temperature control
Integration		3.6	Buggy will have a horn for alerting bystanders and other objects/vehicles
		4	**Performance**
Integration		4.1	The buggy will complete one loop in the parking lot
Inspect		4.2	The buggy will produce less noise than a gas engine.
			Sensors
Integration		5	Speedometer in MPH
Integration		5.1	Must be accurate within +/- 3 MPH
Integration		5.1.1	Battery State of Charge Indicator
Inspect		5.2	Must be accurate within +/- 0.1 V

Figure 5 - Requirements and Test Result

Important test results

Figure 6 shows the expected results and the actual results of the loaded current test of the battery. To relate the throttle displacement to the current coming out of the battery, the motor was run at various voltage levels output by the generator. A multimeter was used to monitor the output voltage of the generator. The throttle was displaced until 100V was read on the meter, and the current coming from the battery was recorded. This was done for each increment of 100V generator output up to 500V to create a basic curve of the current coming out of the battery from low throttle (100V) to max throttle (500V).

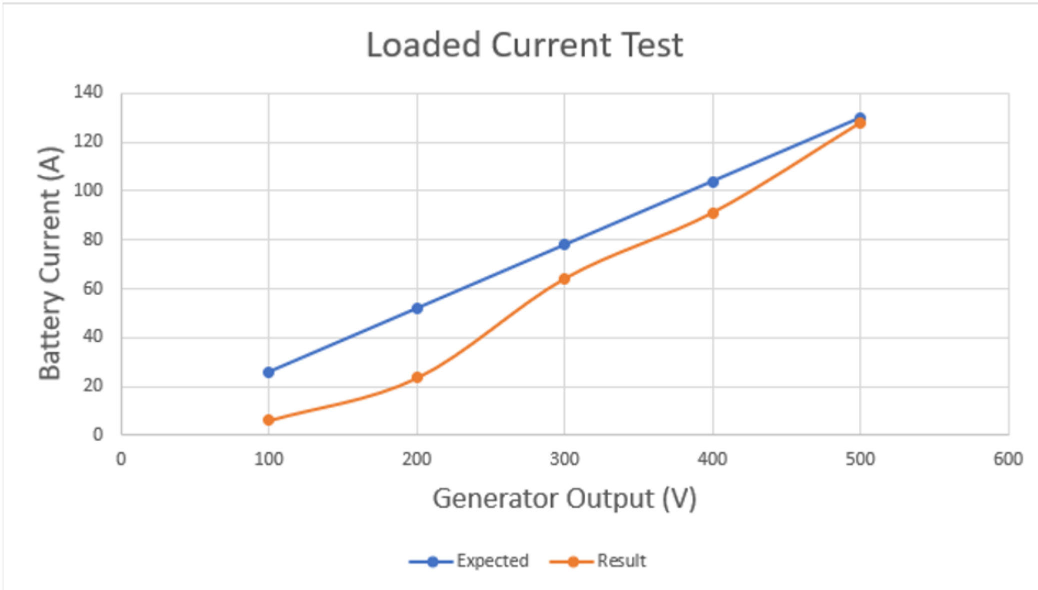


Figure 6 - Maximum Current Test

Figure 7 shows the results of the Longevity Test that was conducted on the battery and system. This test was done to determine how long the battery could power the system under heavy use. It was planned to run for 40 minutes, 10 minutes for each 100V starting at 400V. Unfortunately, the battery could not supply the system for even 20 minutes of operation as the system shut off at 17:36 as indicated by the gray arrow in Figure 7.

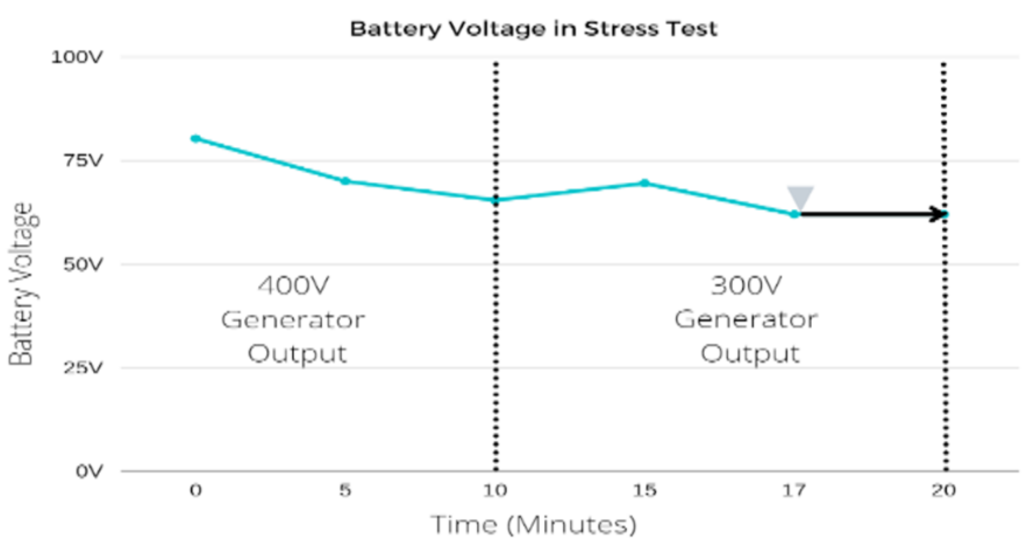


Figure 7 - Battery Longevity Test

Analysis of Results:

Each load test was able to demonstrate key behaviors of the battery. The relationship between throttle position and current from the battery was expected to be linear. Since the battery was only rated for 130A continuous, maximum throttle would equate to 130A or close to it. In the results, the linear relationship was correct. However, the slope of the curve was steeper than anticipated. This meant at low throttle displacements, the current that came out of the battery was lower than expected values. As the throttle was increased, this current came closer to the expected current curve and at max throttle, the current coming out of the battery reached 128A. If the battery is fully charged to 80V, then that means this battery produces over 10kW of power. In a racing application like the SAE Baja competition, the driver will be in that high throttle range for most of the race, slowing down for curves and other vehicles of course. Even if the current is lower than expected in low throttle displacements, it's not likely the system will experience those low currents often when being used.

As for the longevity test, this provided much more insight into the behavior of the battery than the current test. The test was designed to keep the system running starting at a high speed, running for 10 minutes, and then slowing down to a new speed for another 10 minutes. This would be done for a total of 40 minutes, 10 minutes for each speed interval. Considering the client wanted the battery to run for at least 20 minutes, the threshold for success during this test would be 20 minutes. However, as displayed in Figure 7, the battery failed at 17:36 minutes. There are two major pieces of information the team learned from this. One is that the battery of course does not supply the system for long enough. Within the first 10 minutes the voltage rapidly dropped, from a fully charged 80V to 64V. The voltage did jump up by 4V to 68V when the second leg of the test was initiated, but this is due to the regenerative braking charging the battery slightly as the motor slowed down. At a lower speed the battery started to drop voltage again and eventually 7:36 minutes into the second leg, the system shut down completely at 60V. Secondly, the battery doesn't behave like a typical Lithium-ion battery. Typically, Lithium-ion batteries maintain a voltage for most of their charge and then voltage decreases drastically when they have a low charge. That is not the case for this battery, as right from fully charged it quickly was losing voltage. This shows that the cells the team is working with are aging and don't hold much charge. This means that future designs may require a second identical battery to share the load, or will need less aged cells.

Conclusion

Most important requirements and results:

An important requirement for the electric vehicle conversion was to have the battery, the management system, and the motor propel the vehicle for 20 minutes at half throttle. This was no easy task as the weight of the electrical components added a significant amount to the vehicle. In addition to this, the weight of the vehicle was unevenly distributed across the chassis making the center of mass near the rear. Due to the mechanical aspect not being ready for mounting, this requirement was not completely met but was simulated during extensive load testing. A comparable amount of current was drawn from the battery during the load generator test and sustained to simulate driving the vehicle.

Another requirement was an on-vehicle auxiliary system powered by the main battery pack through a DC-DC buck converter. Essentially, the requirement for the converter was to step down 80V to a steady 12V supply that would regulate the taillights, headlights, turn signals, sensors, and brake lights of the vehicle. This auxiliary system was built and demonstrated to be fully functional through isolated and integrated tests. The isolated tests would show each light, turn signal, and sensor to respond correctly to power and switching. The integrated tests took into account the entirety of the circuit and showed the same results as the isolation.

The safety requirement dictated that two kill switches were to be installed, one on the outside of the vehicle for bystanders, and one inside for the driver. These kill switches were to enable the driver to kill the electrical system in the event of failure and for bystanders if the driver were to become incapacitated. The kill switches chosen for this project were breakers that could be flipped to kill the entire system or tripped if there was a massive surge of current. This added a built-in safety factor for the current and manual ability to shut down the driving system. The second safety requirement was to make sure all conductors were not exposed and grounded in case of accidental contact. This included the battery being in a safe location for which it would pose no harm to the driver. These were met with heat shrink, insulating paint, and electrical tape that would insulate the conductors while a thick plate was positioned between the driver and battery.

The last main requirement was to have the vehicle complete one loop around the parking lot to demonstrate basic performance. In electrical means, this requirement met that the battery and its management system functioned properly while powering the motor through the programmed controller. That function was accomplished through dozens of tests and simulations conducted by the team. The mechanical parts of the drivetrain like steering, braking, the coupler, differential, and the driving shaft were not completed. This prevented a true integrated test.

Lessons Learned:

Through the failures and the successes of testing our systems, constructing apparatuses, soldering electrical components, analyzing results, and effecting improvements, many lessons were revealed along the way. These lessons were often derived from problems plaguing different systems and while identifying solutions. Some of the problems during testing included motor controller failures such as overvoltage and undervoltage error messages. The BMS installed on the battery unit has trouble balancing cells during large discharges and continuously causes problems while in operation. Under a heavy load, the battery's voltage has seen to drop from 85% to 0% apparent state of charge.

Another test revealed that the battery's declared 1C rating of 65Ah is not accurate. From testing and age we know the batteries have degraded which shows the importance of purchasing new batteries. Much was learned while using the load platform constructed to scrutinize the equipment. The motor test caused significant centrifugal force that ended with the coupler getting dislodged from the DC generator. The generator had problems with stability in tandem with the motor which led to coupler movement with continuous rotations. This was resolved by adding extra L-brackets to the wooden structure holding the motor in place. Differen't alan wrenches and tools were used to secure the coupler onto the shafts as well as tools for the bolts around the platform. Problems with the curtis motor controller were remedied by reconnecting all the battery management system wires to the terminals of all the cells on each module of the battery. This required crimping new lugs onto wires that were damaged before and needed replacement. This ensured the battery management conductors had secure contact to each terminal. These solutions proved a valuable lesson of basic electronics, troubleshooting, conductor contacts, and trial and error.

One of the main lessons regarding the performance of our battery came from the battery management system. This system is not programmable or traceable to a meaningful degree of information. No paper trail or documentation on its functionality. Aside from the clear aging of the battery, the BMS has trouble charging and discharging the battery and keeping cells equalized. The system should have been removed and replaced from the start with a more robust and competent solution that would allow programming and cell balancing without issues. A great adjustment made caem from noticing the batteries maximum discharge limit of 130A during the 500V generator output test. The controller is designed to pull around 150A continuously which is well above this threshold for the battery. To resolve this issue identified through testing, the throttle has been limited to a 50% degree of motion that would prevent the current from exceeding 130A and damaging the battery. The main lesson from this was to source good materials from used batteries and untraceable systems to new equipment more likely to excel.

User Manual

Introduction:

Thank you for choosing the 2021-2022 eBaja. We hope you like the system. As our society embraces electrification, there is a huge push in the automotive industry to create Electric cars, and this project is a part of that process. The eBaja is a robust system for providing electric car mobility from an electric battery designed specifically for your needs and requirements.

Some key features include:

- Battery
- Motor and Motor Controller
- User Interface with displays and controls
- Auxiliary System with Lights

This user manual includes instructions for you to use and maintain the eBaja electrical system. Our aim is that you will be able to use this system for years to come.
The eBaja Electrification project has been a process of trial and error for our team and as our society embraces electrification we have become more familiar as a team with the demands and difficulties of electrification projects. Our client, Dr. Yaramasu has requested us to produce a working electric vehicle to take the place of a traditional Internal Combustion Engine vehicle from years past. Our project consisted of picking up where another previously left off, working with the battery and motor control system of a prior Capstone project from 2019-2020.

The eBaja runs off of a DC 80V Battery composed of 10 individual LiFePO4 cells, bound together and wired in series. It was constructed by the 2019-2020 eBaja team and can operate the motor control system for the vehicle. The cells are connected to a Battery Management System, which monitors and balances the cells to prevent overheating, overcharging, and damage to the cells of the battery. Additionally, there is a DC Motor Controller which takes input from the driver from throttle and ignition to determine how much power is delivered to the AC Motor to spin the motor and ultimately move the vehicle. The Motor Controller is a complex mechanism that is also programmed to display the RPMs of the motor and allow regenerative braking from the vehicle when the motor is turning without throttle. It also takes throttle from the throttle pedal and directs the correct portion of power to the motor to reflect this.

The Auxiliary Subsystem provides illumination for the vehicle in dark environments. It is powered by the 12V DC-DC Step-Down converter, which takes input 80V from the battery and converts it to 12V for the lights system. The lights function the same as a standard street-legal vehicle, with headlights, back brake lights, and turn signal lights. They can be accessed by appropriate switches located in the driver's compartment, and the ergonomics are consistent with a standard vehicle. Also accessible to the driver is an RPM sensor that reads from the motor controller and a state of charge monitor that reads voltage, current, and state of charge for the entire system. These exist to ensure the driver does not exceed the safe operating parameters of the vehicle unexpectedly and to provide a status for the vehicle's current speed and remaining range.

We tested the strength and endurance of the battery by load testing. This required a platform to raise the motor shaft to the proper height to align perfectly with the generator while remaining completely secured to the platform to prevent disruption of the testing process. Our team constructed the platform exactly to the needs of the motor and generator and is suitable for use in future load tests. Additionally, during load testing we found that two of our battery cells, cells 5 and 6, tend to disconnect from the battery on a whim; when they are properly connected, however, they only lag behind the rest of the battery in voltage by about 5%, which is an improvement. There is another important detail for the energy output of the battery: the current must not exceed 130 Amps. When the current exceeds 130 Amps it risks damaging the battery. To account for this, we recommend limiting the maximum throttle of the vehicle by placing an obstruction to a full rotation of the throttle pedal.

It should be noted that the vehicle was not fully tested as a complete product. Due to difficulties beyond the control of our project, including labor shortages, a global parts shortage, and difficulty in securing adequate welding time for the team of Mechanical Engineers, we were unable to deliver a working final product that was safe to operate and able to operate fully. What we did deliver is a tested electric car motor system ready for use on a vehicle and a load testing platform for future use in eBaja with our motor.

Installation:

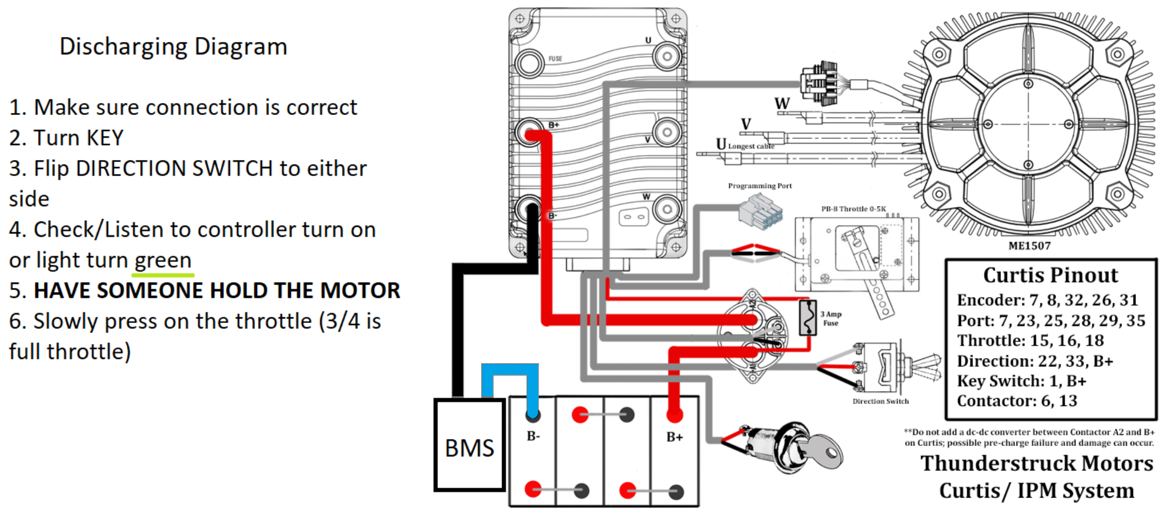


Figure 8 - Motor and controller schematic

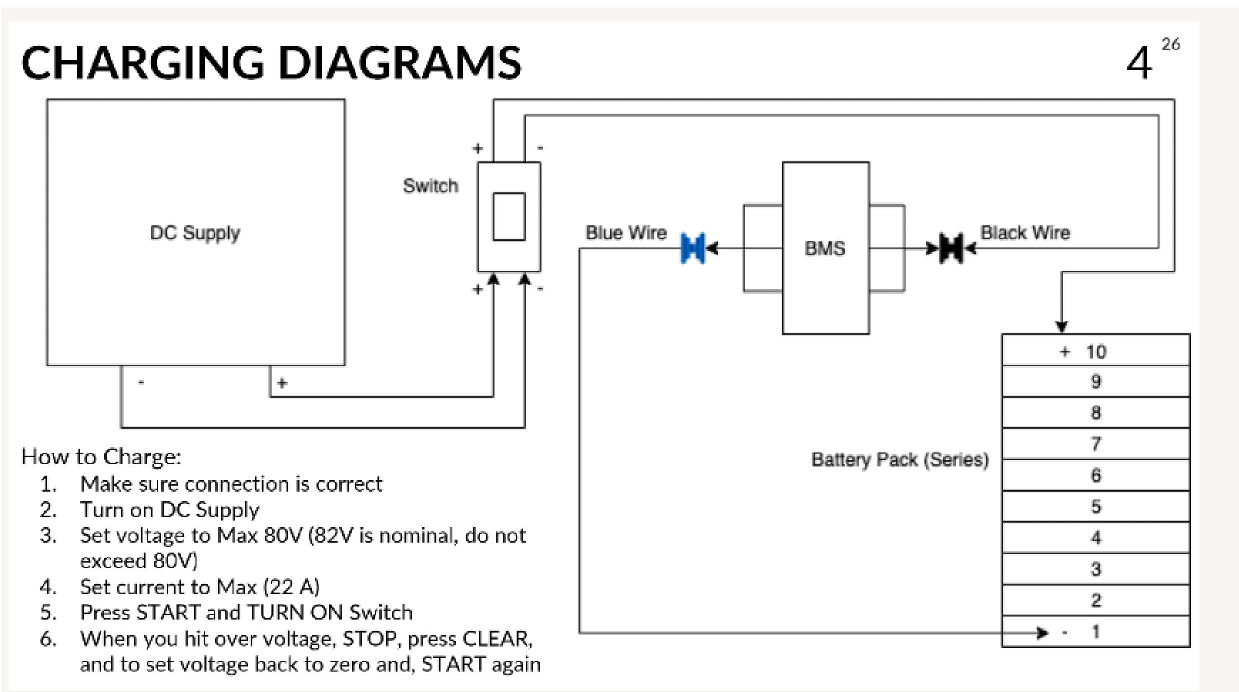


Figure 9 - Battery Charging Diagram

Configuration and Use

The battery is to be carefully handled at all times and all electrical conductors are to be left alone unless otherwise needed. Avoid allowing the battery leads to connect to each other unless specified in the documentation or this manual. This section will highlight the configuration and usage of each component including the BMS, Motor and Motor Controller, Battery, Sensors, and Auxiliary System.

Nissan Leaf Battery Modules:

Each Nissan Leaf module consists of four cells, of which two are in series that are paralleled with the other two cells in series. Since the four cells are paralleled to each other, the cell balancing applies to two cells in each module. The paralleled cells will balance each other while discharging and charging but this is not true for the series-connected cells. The nominal voltage of each module is between 7-and 8 volts. This means multiple stacked module series connections are required and the balancing of these modules is essential to performance and longevity.

Battery management system:

The battery management system is crucial for balancing the series-connected modules which are needed for a functional battery. The BMS has 22 total string attachments. 20 of these string attachments will be used to see the two series-connected cells of each module while the last two strings will be connected to the positive and negative terminals of the entire pack. The stringed wires out of the BMS measure the voltage of the two cells and series and balance them while charging and discharging takes place. If one cell goes higher in voltage than the other, the BMS creates a bypass and balances the cells to make them equal.

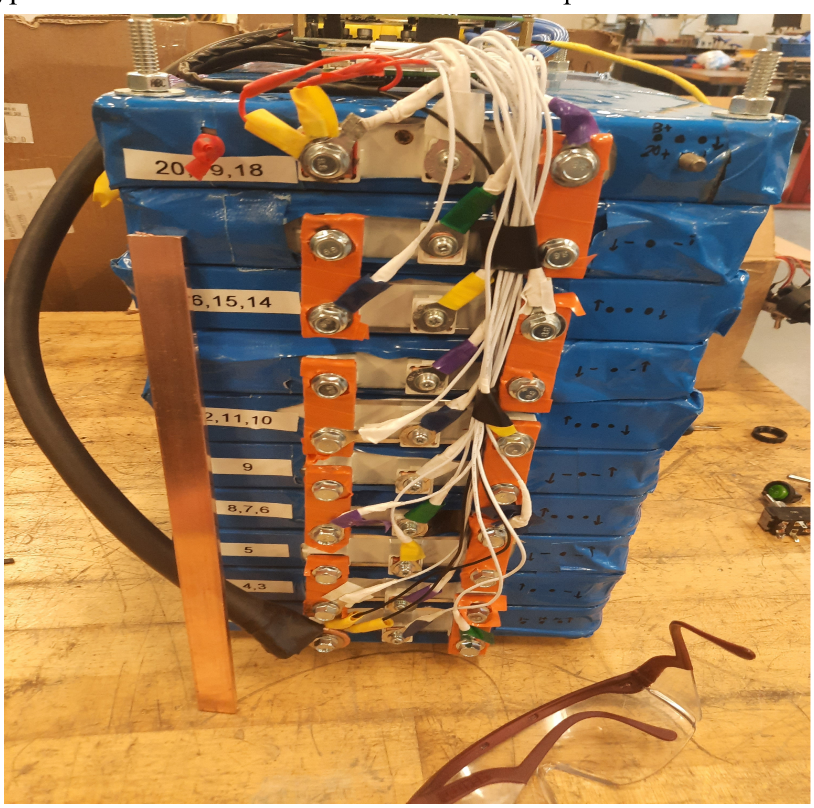


Figure 10 - BMS cell wiring

From the display of the BMS, you can see the amount of current leaving/entering the battery pack as well as the state of charge. This is valuable information for calculating power production and sustainability during operation. The BMS has a toggle switch that provides different screens, from programming to listing all the cells. In particular, the screen that shows the cells is very useful in troubleshooting and determining if the system is functioning correctly. On that view, you can see the voltages of each cell within the battery while charging or discharging, and serves to show the measures being put into account. If any of the cells were to fail the BMS would cease the flow of current to protect the internal cells of the unit.

Motor and Controller:

The motor's main purpose is to take the DC power coming from the battery and convert it to AC to power the three-phase motor while providing full control of the motor during this process. The main control provided is for vehicle motion through the throttle, direction switching of the motor through the forward, neutral, and reverse toggle and the starter switch. The motor is also programmed for regenerative braking while the vehicle is decelerating. While the controller performs many operations, the EnGage II Display shows the RPM and Fault codes for the motor and motor controller, while the State of Charge Monitor shows the voltage, current, and state of charge of the battery.

The throttle is very important and regulates the speed of the vehicle as well as the current drawn from the battery. The throttle, like the starter switch and gear shifter, is connected to the motor controller through separate control lines. The factory control lines for the throttle were very short and thus needed to be elongated through soldering corrected length six-core wire to the controller and throttle. This also had to be done to the gear shifter and starter switch so the driver could operate these controls away from the power system. Starting the vehicle begins with the starter switch which controls the contactor component that bridges the battery to the controller. The contactor is an open or closed switch that can only close to create a circuit once the starter switch is turned in the correct position. This means the driver can only operate the controller once the starter switch is turned, allowing the power system to be operated. Lastly, the gear shifting plays a vital role in changing the direction of velocity. The functions of such are forward, neutral, and reverse. The contactor does have a protection fuse that protects the controller from the event of a surge. This fuse is replaceable and designated for protecting the power equipment from the battery. Below, figure 11, is a chart demonstrating the logical flow of the motor controller system.

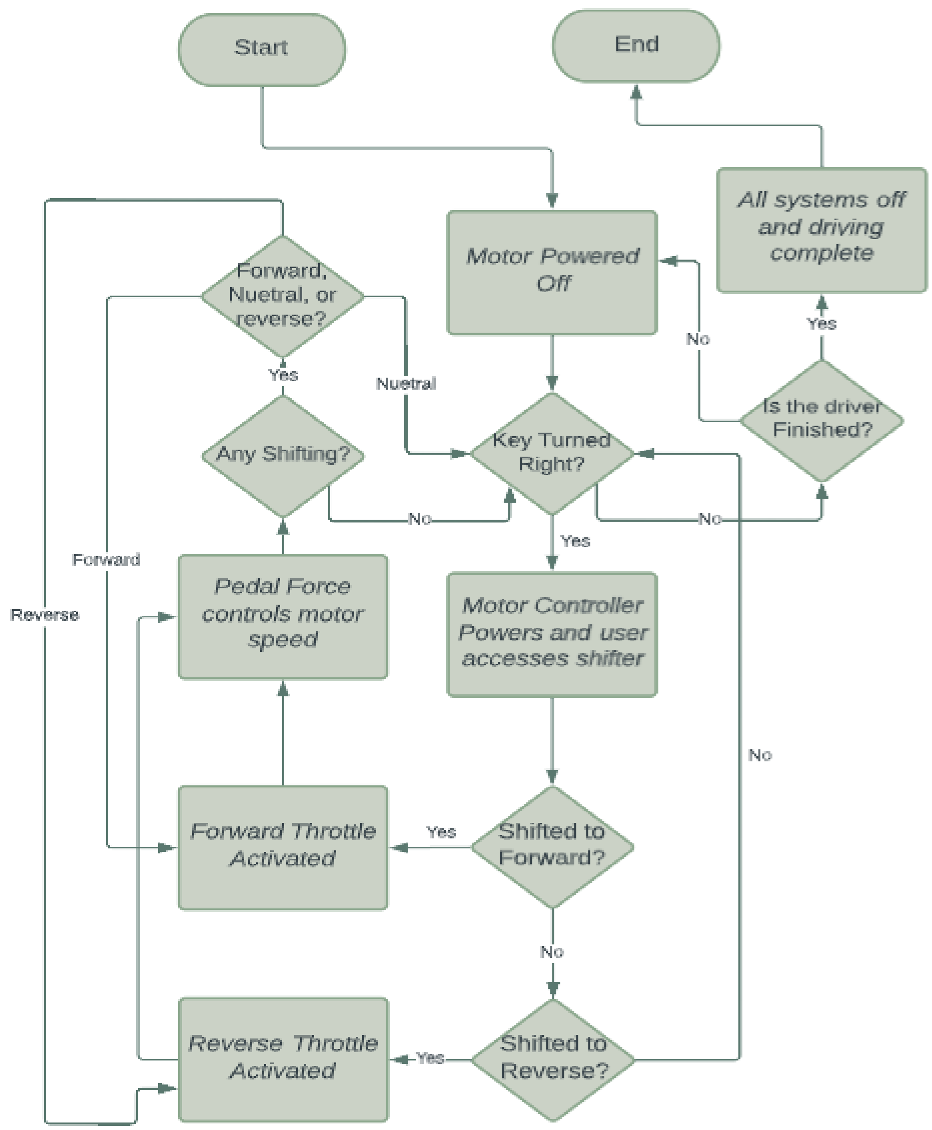


Figure 11 - Motor Controller Flow Chart

Generator Load Test Platform:

This general platform was built to perform simulations of driving the vehicle by putting a heavy load on the motor and discharging the battery at all throttle positions. This served as a foundation for various tests on the motor, the motor controller, and the battery. The layout of this design began by constructing a solid foundation that a large DC generator could be bolted to and leaving room for the Baja motor. Wooden plates were stacked under the Baja motor to line up the shafts of the generator and motor to exact heights from the base. A coupler was then used to secure the shafts together and additional materials such as L-brackets were used to secure the Baja motor in place.

Once all components are secured and the shafts are coupled together, the discharging and circuit schematics need to be followed to wire up the battery to the motor. From here, the starter switch and gear shifter can be turned and the throttle engaged. Power resistors were wired in series on the output of the generator to dissipate energy it produced from the Baja motor driving it. Refer to Appendix B to see the load test platform diagram and how connections were made explicitly. When in use, the diagram needs to be followed, which includes a 300V supply going to the generator to perform correctly. Ultimately, the generator provides a significant load to the motor and the throttle allows the user to vary the load using speed and current discharge from the battery.

Auxiliary:

The Auxiliary System is accessible to the driver through a series of switches in the driver's compartment, located primarily on the dashboard. The lights switch is connected to the forward and brake lights, as well as the low lights on the back turn signals (white wire), while the turn signal switch should be configured with power in the center nodes in the switch and the lights attached to the respective outer connections on the switch for left and right, this will facilitate the blinking signal we expect from a turn signal. The brake switch, not shown, is activated by the brake pedal and enables the red wire for the turn signals on the back as well as the brake lights in the rear of the vehicle. Once the wiring is completed, the auxiliary system is accessible to the driver and enabled whenever the battery is properly set up. The Switch configuration is visible in Appendix C.

Kill Switches:

Safety is the primary factor for the whole project. The vehicle is not to be driven unless it is safe and all measures to ensure its safety have been affected. This was accomplished by the use of two breakers which would be located on the inside of the cabin and the outside. The breakers are wired in series with the output of the battery and can be automatically tripped if a surge of current were to take place outside of natural expectations and manually. Once tripped or flipped, the circuit is open and the battery has no way of producing electricity for the system. The breaker can then be reset once the system is deemed to be operable again. Figure 12 shows a picture of the breaker used in the project.

Figure 12 - Breaker Used for Kill Switching

Sensors:

The main sensors monitoring the system outside the battery management system on the battery are the engage-II motor sensor and the state of charge sensor. These sensors work together to record and display all the information of the power system such as battery discharge power, RPMs, voltage, capacity, and many others. These sensors are used in this way but can be programmed down the road to be more precise with the system. Figure 13 shows the engage-II display that, most importantly, relays RPMs and error codes of the drive system. The state of charge sensor shows the amount of power being drawn from the battery to the auxiliary system and motor while in operation. This sensor contains a current transformer (CT) that fits around the 4/0 wire and measures the current traveling through it. The display of this sensor is run to the front of the vehicle so the driver has a frontal view while driving. This sensor, shown in figure 14, shows the amount of load being imposed, the collective power consumption, and the state of charge of the battery. All this information is vital to the driver while operating the vehicle, for example, if the battery drops below 20% state of charge, then the vehicle should be stopped and the battery recharged.

Figure 13 - Engage-II Display

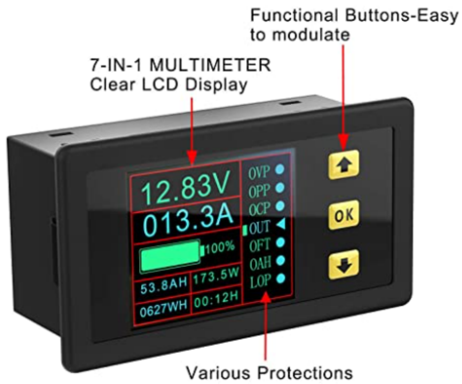


Figure 14 - State of Charge Sensor W/O Current Transformer

Maintenance:

After using the equipment for long periods, wear and tear, and natural degradation is bound to occur. Proper maintenance of all components of the system will prolong the lifespan of the electrical system as well as increase the performance of the vehicle.

Maintenance for the battery is to regularly check all the connections and wiring from all the terminals of the modules and the BMS. The battery should not be left at a maximum charge or at a low state of charge. For optimal health, the battery unit should be discharged and recharged on a regular performance. Best practice would suggest cycling the battery, regularly, from 80%-20% state of charge which would keep the cells in prime condition.

The motor controller maintenance is straightforward and applies after long uses. The engage-II display should be read regularly for error codes or faults happening inside the unit. The temperature should be closely monitored and in the event of overheating a thermal dissipation, a method should be used on the controller to prevent damage. The wires from the throttle, starting switch, and gear shifter should be regularly maintained and insulated for ground fault/shorting prevention. The contact leads on the contactor and controller should be strong and maintained throughout all uses to secure continuity between all conductors. The motor should be maintained by checking lubrication on the shaft, and regularly inspecting the bearings, stator, and rotor of the unit. While running the motor, reduce or eliminate vibrations.

Sensors have constant programming that needs to be checked regularly, as well as calibration of readings that can be referenced to a multimeter or secondary device. The wire length and sizes should be checked for correct current transmission. All the wiring needs to be strong throughout the circuit and secured to the frame or enclosed location.

Lastly, maintaining the auxiliary system starts with the DC-DC converter which must not overheat during use. Heat management and constant inspections must be performed to keep the 12V loads running. Regular removal from the circuit and tests should be performed using a multimeter to demonstrate the constant steady output from multiple supplies. Critically, the DC input and DC output must not be mistaken while wiring the converter.

Troubleshooting Operation:

The first step before troubleshooting is to ensure all connections between all components are correct. Begin by reviewing the battery management system connections to the battery and then the load connections through the management system. Next, make sure the contactor and motor controller are wired correctly according to the schematics on the installation page. The motor will be connected to the motor controller using the inscribed letters U, V, and W and their matched wire length. Lastly, check the appropriate schematic and match all connections for that subsystem accordingly.

Battery Pack:

To begin troubleshooting the battery pack, obtain a digital multimeter and keep the battery management system off. Measure the voltage across the positive and negative terminals of each module individually. This voltage can range from 7.4 to 8 but should all be the same across each module. If one module is off by more than a tenth of a volt, then disassemble the battery. Each module will then have to be charged individually until they reach a uniform maximum charge. If a module does not hold a charge or remain the same as the others, it has failed and will need to be replaced.

After checking the health of the modules, measure the terminals from top to bottom of the battery to get the full series voltage. Turn on the battery management system and verify all manual measurements to be accurate. If the battery management system reads differently then there is a calibration error.

Most importantly, every connection by every conductor needs to be flush with the battery terminals without obstruction. Every wire needs to be insulated and without any bare exposure at any point outside the lugs connected to the terminals. In the event of battery malfunction, turn off the BMS and unscrew all connections. Examine the wires, if there is a tear somewhere along the wire then the wire will need to be replaced with a new lug crimped onto the end. The wires running from the BMS need to be secured/clipped into place. After doing all this, re-screw all connections and repeat these steps. Turn on the BMS and measure the voltage of the battery pack and begin discharging or charging the battery. The battery needs to be regularly charged and discharged for proper health management. Voltage drops are caused by wire sizing and kinks in the system. Ensure that the wire gauge is 2/0 or 4/0 size wire consistent across the main connections.

Motor and Controller

Troubleshooting the controller and motor should be prefaced by the following schematic in figure 8 of the installation section and validating all connections are correct. Additional steps past this will include a multimeter and the installed engage II display that reads all error codes associated with the controller. To begin, remove the battery from the controller and connect a large DC power supply. Make sure the power supply will deliver 78V DC, similarly to the battery, and run the system. If the controller experiences the same problem with a verified DC power supply then you can rule out the battery.

After checking for external factors, examine the engage-II display which is programmed to identify errors within the controller. Powered up to either the battery or DC power supply, watch the engage II display while performing all functions of the controller. Try the throttle in different positions, forward, neutral, and reverse. If the motor controller refuses to turn on then check the continuity of connections and check the fuse connected from the contactor to the controller. Take note of the errors that arrive on the display and refer to this table using the 1236SE manual: https://faultcodes.curtisinstruments.com/list.php?mc=1236SE&action=Submit

Auxiliary

Troubleshooting the auxiliary subsystem is a matter of finding where there is a fault in the circuit if one exists and repairing that fault. It is also imperative that the 12V Step-down converter is properly wired; the step-down converter has three connections: a red wire, a black wire, and a yellow wire. Voltage is fed from the power source (battery) to the red wire and ground through the black wire; the actual 12V Auxiliary components must be fed power through the yellow wire, and then grounded to the same location as the step-down converter's black wire.

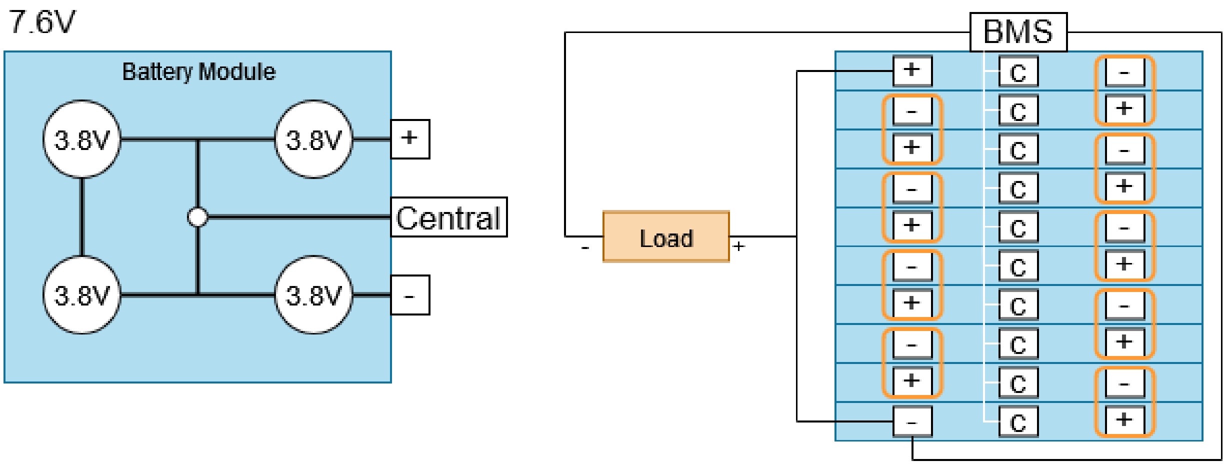
After checking that the step-down converter is wired properly, make sure the lights are wired properly. The Auxiliary system wiring overview can be found in Appendix D, and the lights wiring instructions can be found in Appendix E. Each light must be properly wired to its appropriate switch for the sake of driver controls.

Conclusion:

Researching, testing, building, and learning were critical parts of this project that remained constant throughout it. Beginning with analyzing the internal chemistry of each module and cell layout of the battery, programming the sensors and motor controller within specific parameters, and finally creating the electronic system for an electric vehicle. The project utilized information learned over the course of four years by turning theoretical concepts into hands-on experiences.

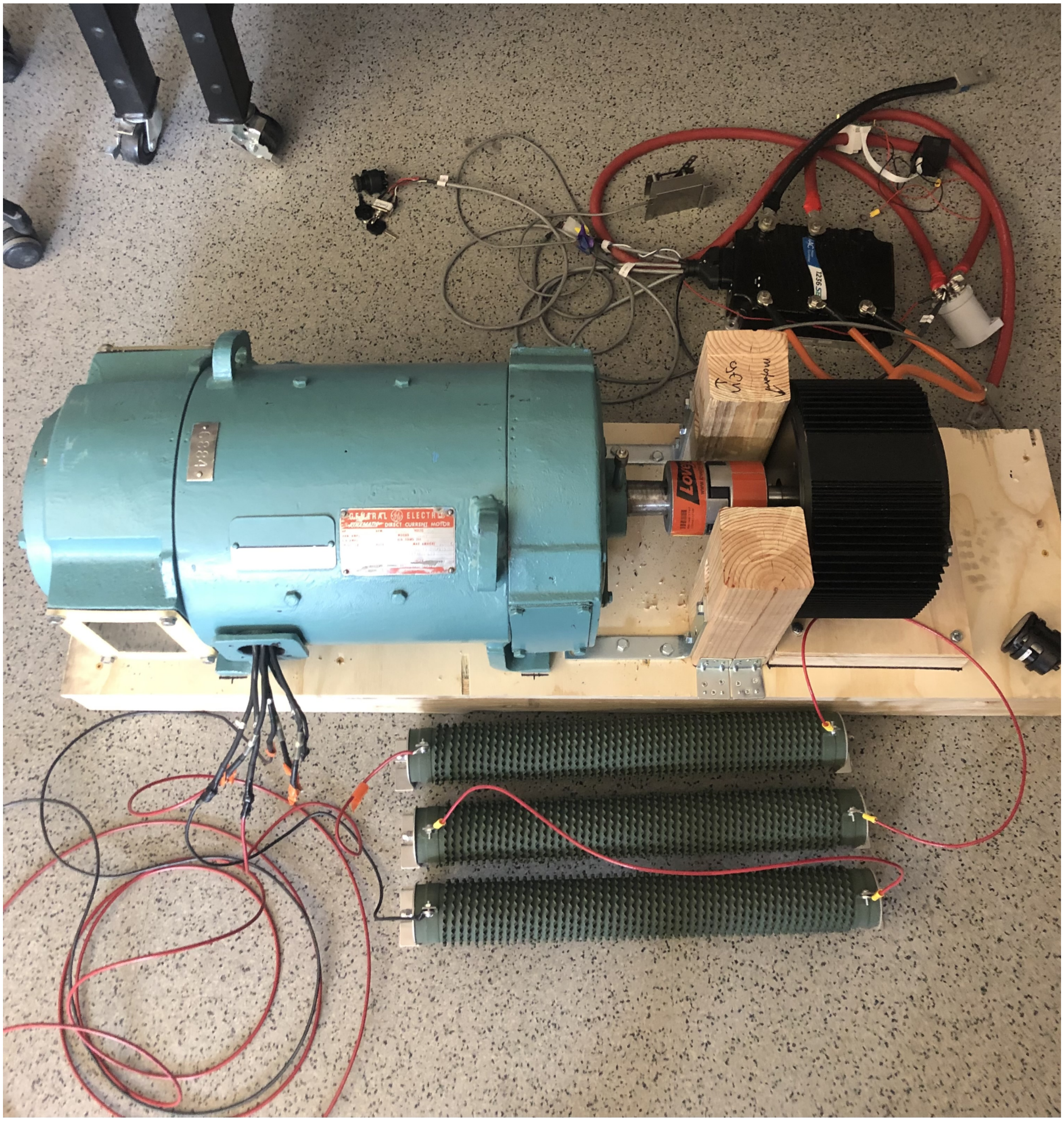
All that remains is an integration onto a functional drivetrain and chassis that would put the electrical system under a true vehicle load. Despite this absence, the generator load test was a suitable simulation that proved the battery could deliver large amounts of current continuously through the motor. The contents of this report will serve as an excellent guide for our successors and NAU's first working electric vehicle.

Appendix A - Battery Schematic



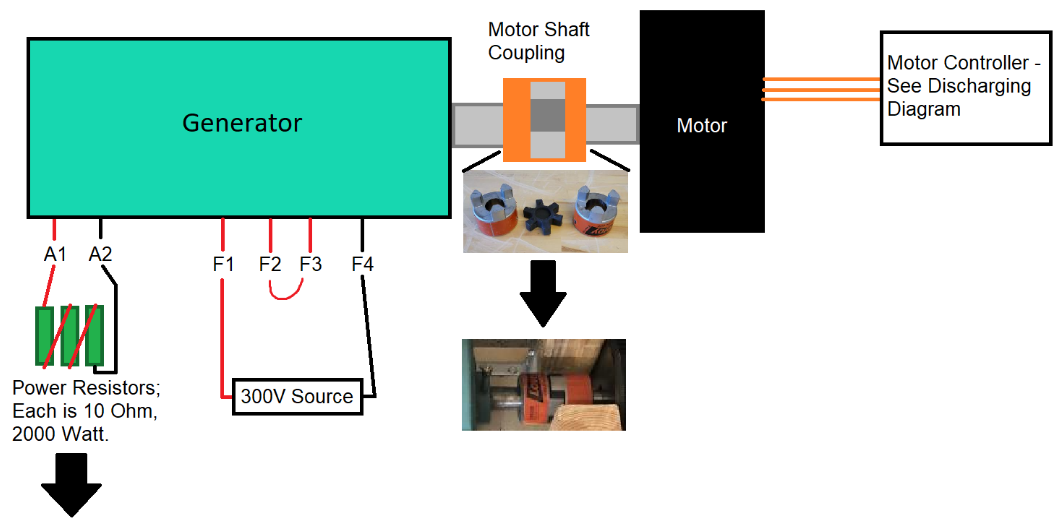
Left: single Nissan Leaf battery module
Right: Ten modules forming 80V Battery Pack for the vehicle

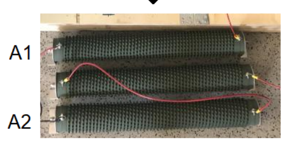
Appendix B - Load Testing Platform



Appendix C - Generator Load Testing Diagram

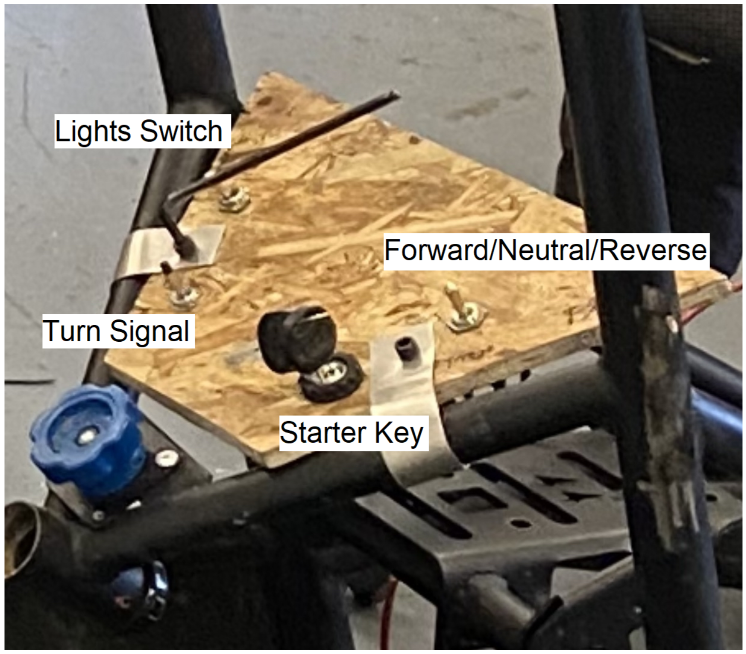
Generator Load Testing Diagram



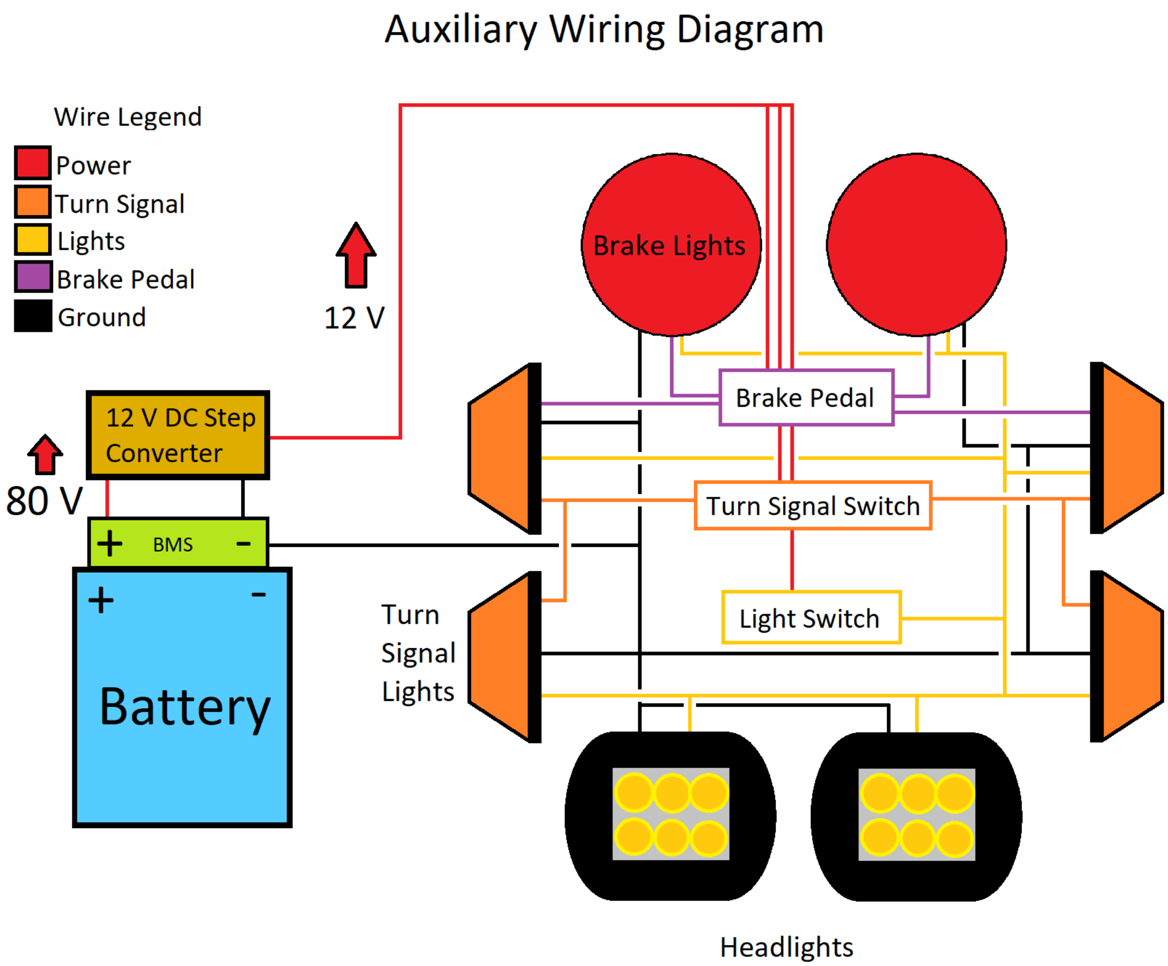


1. Tighten Motor Shaft Coupling
2. Tape Metal connections to prevent shock
3. Use motor shaft keys
4. **DO NOT** exceed 300V Armature voltage
5. **DO NOT** spin the generator without both Power Resistors AND Armature Voltage
6. Make sure the motor is securely fastened to platform before running

Appendix D - Auxiliary Switch Configuration



Appendix E -Auxiliary Lights Wiring Diagram



Appendix F - Auxiliary Wiring Method

Rear Light Wiring

Red Wire - Brake Light (Bright) (+)
Black Wire - Rear Light (Dim) (+)
White Wire - Ground (-)