AuE 8150 Electric and Hybrid Powertrains

Final Report – Battery Pack Design

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Background

Connecting battery cells in series and parallel effects the performance of the battery pack and overall packaging of the final product. Battery cells connected in series add voltage while maintaining a constant capacity, whereas parallel connections add capacity with a constant voltage. Battery packs for transportation applications must include a combination of series and parallel applications to meet the required demands of the user. Series connections are beneficial for increasing the voltage output of the system, whereas parallel connections are useful for extending the battery life for a given application.

However, the final configuration must be packaged with appropriate safety features, such as cooling fans and a battery protection unit to prevent over charging and over discharging. The final dimensions of the battery pack will heavily influence the final end-product design, both in terms of weight and size. If the battery pack is not used for a given product, the design and operation of the pack can provide fundamental and applied insights into the design, physics, and usage of individual, low voltage and low capacitance cells working in tandem to achieve power certain objects.

Problem Statement

In this project, a battery pack will be designed using prismatic battery cells. Each battery cell is 2.4 volts and 20 Ah. The goal is to design four 12-volt modules that can be connected in series to produce a 48-volt battery pack. Each module can also provide voltage and can be charged and discharged independently. Specifically, the project will:

1. Provide a design configuration topology for each module with measured readings confirming the target voltage of 12 volts per module.

2. Ensure safety with a temperature sensor to actuate a cooling fan and protection unit to prevent overcharging and over-discharging.

3. Achieve the target 48 volts with the final battery pack.

4. Test an individual 12-volt pack in the Arbin.

Literature Review

Assembling battery packs have a long history in the DIY (do-it-yourself) space. For hobbyists, these projects usually involve connecting small battery cells equivalent to AA batteries to deliver power for other custom DIY projects **Error! Reference source not found.**], **Error! Reference source not found.**]. The idea of modular packs that can be accumulated together to deliver high voltage for varying applications is not a new concept.

Automotive battery packs are commonly designed in a pack-module-cell structure. The actual designs differ mainly on how the desired pack capacity and power are achieved. One may connect fewer large battery cells with a high individual cell capacity in series. Alternatively, multiple small battery cells with low individual cell capacity can be connected in parallel and subsequently connected to modules with high capacity. Mixed types where series and parallel connections are combined also exist. Parallel connections ensure the highest capacity and amperage requirements, whereas series connections are used to enhance the supplied power [3]. The two approaches can be comprehended when considering the batteries in BMW’s i3 and Tesla’s Roadster. In the latter case, the pack consists of 11 modules connected in series. Each module is built of 9 sheets, connected in series. Each sheet consists of 69 individual cylindrical cells connected in parallel with an individual cell capacity of 2.16 Ah [4] [5]. This cell configuration is designated 69p9s11s, where *p* and *s* refer to parallel and series connections, respectively. On the contrary, BMW’s i3 connects 96 prismatic cells with an individual cell capacity of 60 Ah in series, whereas they are physically built into 8 modules of 12 batteries each and thus designated as 12s8s [5]. Building a system with fewer large cells, as in the BMW i3, decreases the overall system complexity. At the same time, large cells limit the design flexibility of the pack. However, large, and more complex battery systems as applied by Tesla, for instance, enhance the system’s reliability in case of an open wire failure [5].

Mechanical phenomena play an important role when it comes to battery module operation and safety requirements. During operation, battery modules are exposed to dynamic loading and random vibrations, which may cause short circuits and fire [6]. Random vibrations have a particularly high influence on modules with many single cells due to their periodic structure. The module's structural dynamics can be impaired as a high modal density in many frequency ranges is promoted. Moreover, the battery interconnection joints will to some extent be pre-stressed due to the interconnecting by joining which may, in turn, affect the dynamic response of the entire battery pack noticeably [7]. Lithium-ion and polymer batteries generally behave dynamically in terms of structure and dimension during charging and discharging [8] which has a recognizable impact if the casing is soft. The reason for expanding during charging and contracting during discharging is a lattice expansion or contraction of the host material. This effect can remain permanently due to an irreversible expansion of the electrode, and dead material and pressure changes in the cell [8].

When interconnecting batteries regardless of the joining technology and the electric circuit type, i.e., parallel or series connection, one will unavoidably obtain a joint with an inherent electrical resistance. This resistance will occur at the connection point between battery and interconnector. This resistance is here designated as connection resistance. During charging and discharging of a cell, module, or pack the existence of a connection resistance has two direct effects, namely loss of electrical energy across the interface and heat generation in the contact region, where both depend on the resistance. The loss of energy will directly influence the battery performance, as during charging and discharging introduced energy will be partially dissipated, which in turn reduces the available battery module capacity. In other words, the larger the resistance, the more energy will be dissipated, and thus less energy can be used to propel a car, i.e. the possible range is shortened [9].

The cooling system for a battery pack can also drive uneven temperature distribution. If the cooling media, typically air or liquid, significantly increases in temperature as it flows across the pack or does not cool some parts of the pack as effectively as others, there will be a temperature distribution across the cells. In [10] the liquid cooling system caused a 4°C temperature variation between cells in a 4S pack and resulted in a 1% variation in voltage between the cells during operation. The non-uniform temperature was shown to cause a 25% difference in current for two parallel connected cells in [11] and to cause 5% additional aging for a temperature distribution of 5°C in [12]. Cooling systems should therefore minimize the temperature variation across the pack, ideally keeping the hottest and coolest parts of the pack within a few degrees Celsius of each other. Many scholars have done some research on forced-air convection. Li et al. [13] investigated the influence of air inlet angle, air outlet angle, and battery spacing on the maximum and minimum temperature of the cells. Multiple iterations are often utilized to obtain the optimal local scheme of the air-cooling heat dissipation structure. Fan et al. [14] reported that improving the spacing of cells to some extent would enhance the uniformity of battery heat distribution but increase the maximum temperature of the cell in the meantime. Wang et al. [15] studied the effects of the width and the ventilation location on the heat dissipation of the batteries. Mahamud and Park [16] demonstrated that the reciprocating airflow for cooling would improve temperature uniformity and reduce cell temperature.

This paper aims to provide an overview of interconnecting battery cells when designing battery packs. In the following sections, the approaches used will be summarized, along with an idea of the battery pack design of a four 12-volt module connected in series to obtain 48-volt as an output.

Design of 12V Battery Pack

The approach behind this project is to produce four identical modules from prismatic cells of 2.4 volts and 20 Ah. Each module will contain ten prismatic cells with two cells connected in parallel, providing a total capacity of 40 Ah. The five pairings are connected in series to provide a target voltage of 12 V per module. Each module will have a temperature control switch to actuate a fan if the temperature increases beyond a certain limit and a protection unit to prevent overcharging and over-discharging. Table 1 lists the required components, quantity, and source.

Table 1: List of components, quantity, and source

Component Name	Quantity	Source
W1209 Temperature Control Switch	4	Amazon
12 V DC Fans	4	McMaster
Heat Wrap	2	Amazon
Battery Protection Unit	4	Amazon
Box	4	Provided
Wire	-	Provided

The final battery pack consisting of the 4 modules is shown in Figure 1. The final voltage of the battery pack was 44.9 V, which is just short of the target 12 V. Each individual cell contained a voltage around 2.2 V, which gives each module a voltage of ~11 V. Although some individual cells clearly labelled the voltage as 2.4 V, online research of the cells revealed that some identical units featured a voltage of 2.3 V, which would result in a final 46 V. To remedy this issue, two more cells per module can be connected in series to increase the module and battery pack voltage to 13.6 V and 52.8 V, respectively. For this demonstration, the modules were connected with simple blue wire to measure the final voltage. Depending on the application, thick wire would need to be specified if the current draw is significant.

Figure 1: Final battery pack with four modules connected in series. The blue wires are connected to each individual module.

Heat wrap was not used in the final design because it was too small to cover the final module length. The 12 V DC fans were installed into the plastic box by cutting a segment along the length to mount the fan with set screws. Each individual cell contained a small black strip that would provide an air gap for cooling. Each temperature sensor was simply taped to the end of each module, and the control board for the temperature sensor was also taped onto the side of the plastic box. The temperature sensor could be externally powered through a 12 V supplied or powered with the battery. The temperature at which the cooling fan will turn on can be set by the control board. In testing charging and discharging with the Arbin, it was found that a charge/discharge current of 20 A did not significantly increase the temperature of the battery pack above 25°C. When the temperature threshold was set to 23°C, the cooling fan was able to effectively cool the battery pack to ~21°C. The final module design is shown in Figure 2.

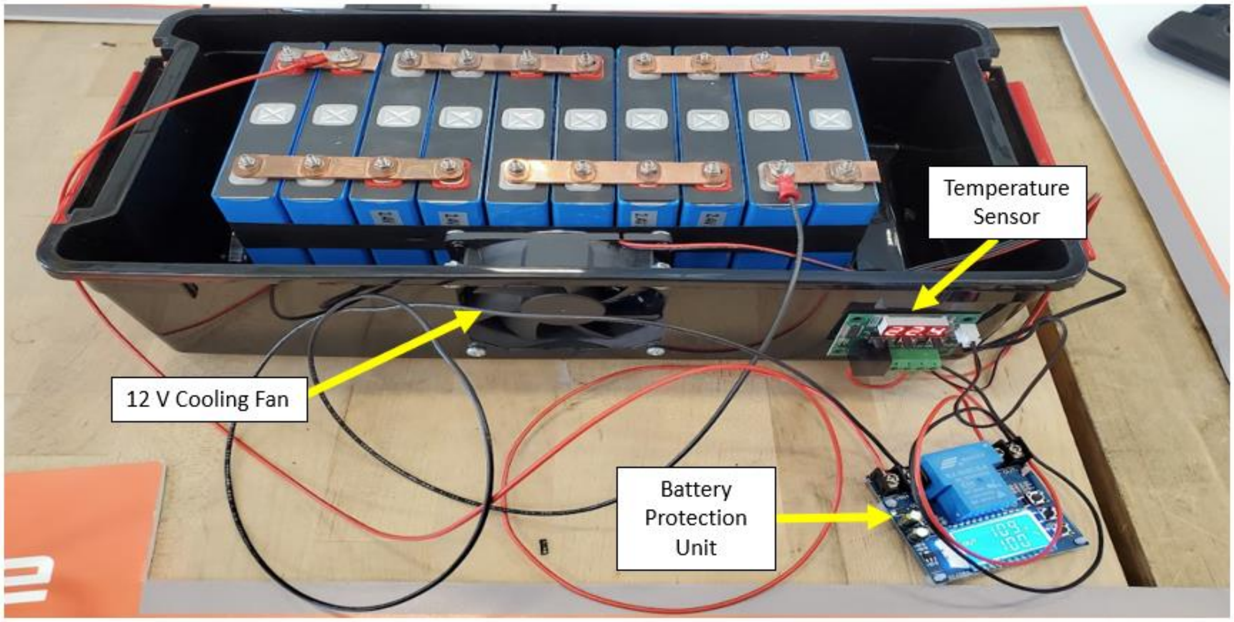

Figure 2: Module design with battery, cooling fan, battery protection unit, and temperature sensor.

The battery protection unit acts as a switch to protect the battery under charging and discharging scenarios. The protection unit is connected to the battery pack, with the charging source or discharging source connected to the other set of terminals. In Figure 2, the battery is providing voltage, passing through the protection unit to power the 12 V cooling fan. Once the voltage of the battery, displayed in Figure 3, falls below a certain limit set by the user (in this case 10.8 V), the protection unit will switch voltage off to the cooling fan, thus protecting the battery from excessive discharging. The protection unit was shown to work under discharging action, but has not been tested for charging since the Arbin was used to charge the module.

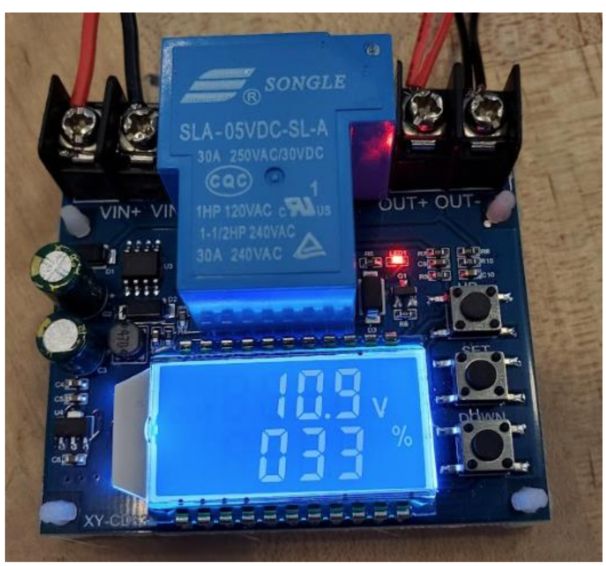

Figure 3: Battery protection unit display screen.

The final set of testing involved charging and discharging using the Arbin. The schedule was set to discharge for 15 minutes, rest for 10 minutes, and charge for 15 minutes. The discharge and charge current was set to 20 A. An individual module was connected using thick gauge wire to ensure sufficient safety with the tested current, which is shown in Figure 4. The battery voltage and current measured during the Arbin test is shown in Figure 5. Under these testing conditions, it was found that the cooling fan was more than sufficient for maintaining the set temperature. The battery protection unit was not used in this testing due to safety concerns regarding the gauge of wire required to adequately pass a current of 20 A.

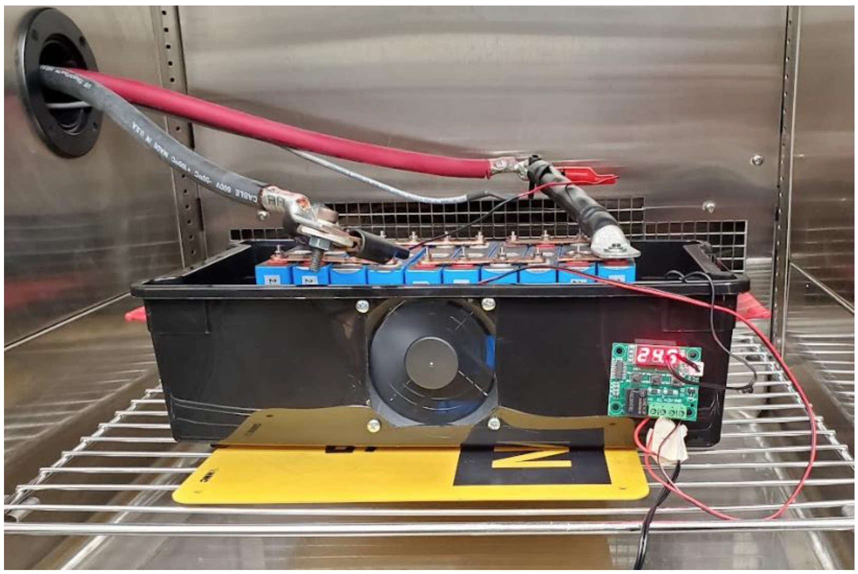

Figure 4: Arbin test set up with battery module, temperature sensor, and cooling fan.

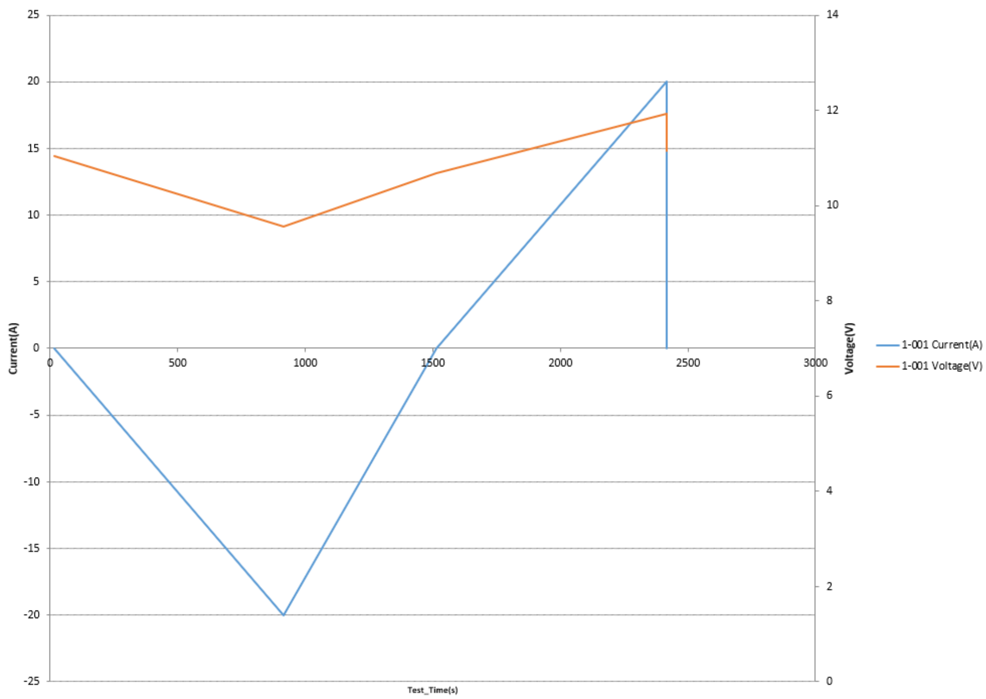

Figure 5: Voltage and current of battery module during Arbin test.

Conclusions

In this project, a battery module was design and fabricated such that multiple modules could be connected in series to achieve a higher voltage output. The final outputs of the project are as follows:

1. Four 11.2 V 40 Ah battery modules were fabricated using prismatic cells, a container, a temperature sensor, and a battery protection unit. The measured voltage of 11.2 V was slightly lower than the desired voltage of 12 V, likely due to a mismatch of specification from the labelled cells. In the future, this can be remedied by adding two additional cells in series to each module to achieve ~13 V.

2. The temperature sensor was tested in the individual battery module. During Arbin testing, the cooling fan was sufficient at maintaining the module temperature below 23°C.

3. The four battery modules were connected in series and produced a voltage of 44.9 V. Again, this was slightly less than the desired voltage of 48 V.

4. An individual module was tested in the Arbin at a charge and discharge current of 20 A.

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