Safety and Battery Management Systems within an Electric Personal Watercraft

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Word Count - 6426
Date of Submission – 19th November 2017

1 PROJECT SUMMARY

The University of Western Australia's Renewable Energy Vehicle (REV) Project is an initiative aimed at revolutionising personal transport. It is run by a team of staff and students focussed on the relationship between transport and long-term sustainability. The fundamental aim of this project is to build vehicles with zero emissions through the conversion of fossil fuel powered engines and motors into units that are powered by renewable electrical energy, through the implementation of grid connected solar panels.

Beginning in the second half of 2012, one such project under the REV umbrella has been the REVSki project. An ordinary internal combustion engine Jet Ski is a large source of emission and noise, therefore, the aim of this particular REV project is to construct an electric Jet Ski resulting in reduced sound pollution and, more importantly, eliminating emissions. The Jet Ski, a Sea-doo GTI130 purchased without a motor or fuel tank, requires certain safety systems to protect both the user and the expensive electrical components that are critical to operation.

For the duration of 2017, the end objective had been to install a battery management system to protect the batteries from being damaged by overcharging or by discharging too low. Additionally, the wiring configuration of an existing insulation monitoring module had been reconfigured to work in conjunction with the battery management system, forming a safety system for the user and electrical components. A voltmeter board containing 8 voltmeters was used to record the voltage readings of the battery cells over the course of a single charge and discharge cycles. This was both to prove that the battery management system operated as intended and to observe whether voltage drift of the battery cells was significant, which would influence any suggestions on actions for future work. The results that the team acquired has shown that the BMS cuts power when the voltage of the cells reach the lower and upper thresholds. The REVSki Safety System performs as required, however the results have drawn attention to the impact that cost has on the effectiveness of the project, with many leftover batteries showing varying signs of damage and leftover capacity. The REVSki would benefit in future from the addition of temperature and water sensors into the safety system and would greatly benefit from the replacement of all batteries installed prior to 2016 due to their damage.

2 LETTER OF TRANSMITTAL

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19th November, 2017

Winthrop Professor John Dell
Dean
Faculty of Engineering, Computing and Mathematics
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Dear Professor Dell

I am pleased to submit this thesis, entitled "**Safety and Battery Management Systems within an Electric Personal Watercraft**", as part of the requirement for the degree of Master of Professional Engineering.

Yours Sincerely

Jayden G. Dadleh
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3 ACKNOWLEDGEMENTS

I would like to begin by thanking my supervisor, Professor Thomas Bräunl, for his support throughout the course of my final year project. The guidance Professor Bräunl has provided has been heavily influential on raising the quality of work within the REVSki project and aiding the team in reaching all of the project deadlines.

For playing a huge part in making the project possible, whether that be procurement of components through sponsorships, continued general assistance or open communication, I would like to express my gratitude to the sponsors supporting the REV project and, in particular, the REVSki.

I would also like to thank Marcus Pham and Michael Stott for making themselves available in answering any questions the team may have had and aiding in solving any issues that arose throughout the year.

Finally, I would like to thank Mark Henderson and the team within the ECM Workshop for providing technical insight and assistance when needed.

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7 NOMENCLATURE

DOD	Depth of discharge
SOC	State of charge
BMS	Battery Management System
REV	Renewable Energy Vehicle
A	Amperes
V	Voltage
IMD	Insulation Monitoring Device

8 INTRODUCTION

Global fossil-fuel carbon dioxide emissions has seen a steady increase alongside the development of countries all over the globe, with over 400 billion metric tonnes of carbon being released into the atmosphere since 1751 (Boden, Marland & Andres 2017 [1]). According to Boden, Marland and Andres [1]; with the increased consumption of fossil fuels, approximately half of these emissions has occurred since the late 1980's. Figure 1 presents the metric tons of carbon emissions per year.

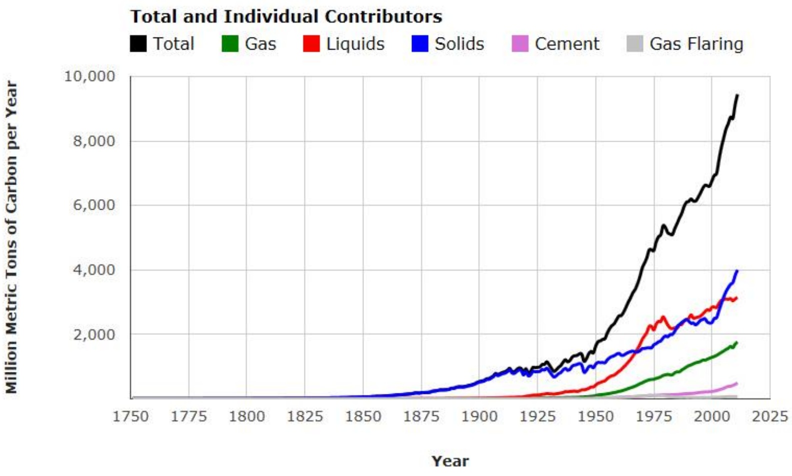

Total and Individual Contributors

Figure 1. Million Metric tons of carbon per year. Note: From Global, Regional and National Fossil-Fuel CO2 Emissions, 2017.

According to the Australian Department of the Environment and Energy (2015 [2]), transport was responsible for approximately 5% of Australia's total carbon dioxide emissions [2]. Due to this share, transport has become an area of focus for improvement, with research into electric transportation on the rise as the stock of electric cars surpass 2 million as of 2016, as can be seen in Figure 2 ([3] International Energy Agency 2017).

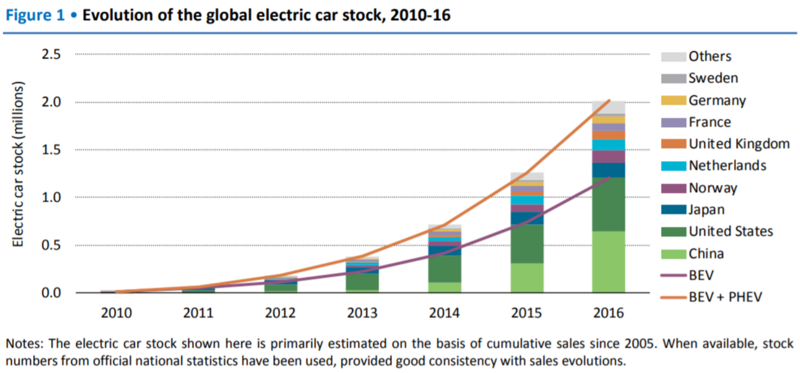


Figure 1 • Evolution of the global electric car stock, 2010-16

Notes: The electric car stock shown here is primarily estimated on the basis of cumulative sales since 2005. When available, stock numbers from official national statistics have been used, provided good consistency with sales evolutions.

Figure 2. Annual Electric Car Stock. Note: From Global EV Outlook 2017 – Two Million and Counting, 2017.

With the increasing interest in the electrical vehicle market, The University of Western Australia launched the Renewable Energy Vehicle (REV) Project in 2008. In particular, launching a unique project in the form of the REVSki in 2012; Australia's first personal watercraft, commonly called a jet ski, to be converted from an internal combustion engine into an electric-powered motor (The REV Project 2017). The REVSki is a Sea-Doo GTI 130hp model Jet-Ski that can be seen in Figure 3.

Figure 3. Sea-Doo GTI130 - the shell of the REVSki.

8.1 ELECTRIC VEHICLES IN A MARITIME ENVIRONMENT

As can be imagined, a maritime environment is a dangerous location for electrical components, with greater exposure to corrosion and the possibility of electrical faults and shorts, as well as general water damage. As the REVSki is measured at a length of 3.4m and a watercraft, the electrical installation of the REVSki are required to satisfy the Australian and New Zealand standard, Electrical Installations – Marinas and boats – Boat Installations (2014), which specifies the "requirements for the design, construction and installation of electrical systems in boats that have a length of up to 50m."

Detailed by the above standard, it is required that all conductor connections shall be within enclosures rated to an IP 55 minimum (Clause 7.3.2 Standards Australia 2014). It also states that "a protective device shall automatically disconnect supply to the circuit in the event of a fault between a live part and an exposed non-current-carrying conductive part." (Clause 4.2 Standards Australia 2014) In order to satisfy this particular clause of the standard, an insulation monitoring device had been previously implemented into the REVSki, capable of acting as the protective device, ensuring the users safety, especially within the conductive environment of water. The operation of the implemented insulation monitoring device will be covered in a later section.

8.2 BATTERY PROTECTION WITHIN AN ELECTRIC VEHICLE

The batteries used within the REVSki are Lithium Iron Phosphate (or $LiFePO_4$), in particular, the Headway 38120 3.2V 10Ah battery cells. These cells within the REVSki are the most expensive components sourced at $26.50 per unit (EVWorks 2017). With 240 battery cells configured in a 30 Series and 8 Parallel configuration, this exceeds all other electrical components at a total of $6360, an example of a single battery tube containing 7 series and 8 parallel can be seen in Figure 4.

Figure 4. 7S8P battery tube used within the REVSki.

Due to this significant cost, it is imperative that the REVSki possesses a system that is capable of monitoring and managing the batteries and preventing damage to the cells that could be caused by overcharging or over discharging. This system monitoring was also employed to ensure that the batteries perform as is required, allowing the individual cell voltages to be read and recorded, allowing further results to be determined. The details of the battery management system will be explored in a later section.

8.3 PREVIOUS PROJECT INSTALLATION

The major issue to be rectified was that of the previous wiring and installation of the safety system's electrical components. The REVSki project has had three teams working on it, prior to 2017, one of those having installed the insulation monitoring device. Conversely, the previous team had not managed to completely install the battery management system, simply installing the architecture but not completing the wiring to allow functionality of the BMS. The ultimate aim of an effective safety system for a jet ski requires these systems to be wired in series with one another, this then requires that all individual modules, such as the insulation monitoring device and the BMS, forming the safety system must be operating within satisfactory limits before operation of the jet ski is able to commence.

9 LITERATURE REVIEW

9.1 THEORY

This section of the report will expand upon the information presented in Section 8 by providing an explanation of the components that will form the safety system of the REVSki; the insulation monitoring device and battery management system. By presenting the functionality of the individual components, the reader will be provided with a stronger foundation to understand how these components will operate in the context of the REVSki itself. After an analysis of the literature pertaining to the safety system has been conducted, this literature review will finish with the theory behind many of the decisions made throughout the design and construction phase of these components.

9.1.1 Insulation Monitoring Device

As the REVSki project is a proof of concept for the future of electric powered recreational watercraft, one of the issues to overcome was that of safety for the user and satisfying any Australian standards relevant to electrical systems in a maritime environment. Implemented by Joshua Knight, a previous REVSki team member, many of the requirements set by the standards have been met by Knight's design, however, the standards that are required shall be reiterated for clarity. (Knight 2015)

The REVSki, as previously mentioned, contains 30 battery cells in series at 3.2V per cell, resulting in a total system voltage of 96V. The Australian and New Zealand standard, Electrical Installations – Marinas and boats – Boat Installations, states that the scope covers "direct current systems that operate at a nominal voltage not exceeding 1500V" and as such, the REVSki falls within this scope. The standard also states that "a protective device shall automatically disconnect supply to the circuit in the event of a fault between a live part and an exposed non-current-carrying conductive part." (Clause 4.2 Standards Australia 2014) In the event that an insulation failure occurs over a current carrying conductive part, such as wire damage, and contact is made between this live part and non-current carrying conductive parts, a protective device must be used within the REVSki that is capable of cutting all power.

The REVSki must also accommodate protection against direct contact with live systems through the use of enclosures. The Clause 7.1.1 of AS/NZS 3004.2-2014 specifically states that "live parts shall be protected against accidental contact by the use of enclosures in accordance with Clause 7.1.1. All exposed non-current carrying parts shall be connected to earth either via the protective conductor or by connection directly to the hull of a steel boat." The enclosures to be used, as previously mentioned, shall be rated to a minimum of IP 55 in accordance with Clause 7.3.2 (Standards Australia 2014).

Finally, there is a requirement for the REVSki to possess an earthing electrode under section 7 of AS/NZS 3004.2-2014. It states that "the protective conductor shall be connected to an earthing electrode that comprises a solid uncoated conductor having a contact area with the water of at least 0.1 m^2, a thickness of at least 5 mm and a width of at least 20mm secured to the outside of the hull in an area reserved for this purpose and located below the light-load water line so that it is immersed under all conditions of heel." (Clause 7.1.2 Standards Australia 2014)

As calculated by Joshua Knight (2015), the protective device must be capable of detecting earth faults of "less than 30mA." The protective device used within the REVSki and implemented by Knight is a Bender Isometer IR155-3204 Insulation Monitoring Device. This device is capable of monitoring the resistance of the insulation between the current carrying conductive parts and the REVSki earth and, if the resistance is above a level of 500ohm/volt, will provide an OK output which should be capable of switching the 96V circuit open or closed (Bender 2016). The following equations calculate the maximum allowable fault current detectable by the Bender module.

$$V = IR$$

$$V = I(500 \times V)$$

$$1 = I(500)$$

$$I = \frac{1}{500} = 2mA$$

As the Bender module maximum earth fault is a current of 2mA, it easily satisfies the 30mA requirement. The Bender module used can be seen below in Figure 5.

Figure 5. Photo of Bender IMD taken within the REVSki laboratory.

The Bender module is coupled with an earth electrode which ensures that any faults dissipate to the surrounding water. The electrode was manufactured to satisfy the requirements of Clause 7.1.2 of AS/NZS 3004.2-2014 while also being in a convenient position. This meant that the electrode was in the form of a plate designed to be mounted to the cooling plate located at the stern of the REVSki, underneath the impeller. The schematics can be seen below in Figure 6.

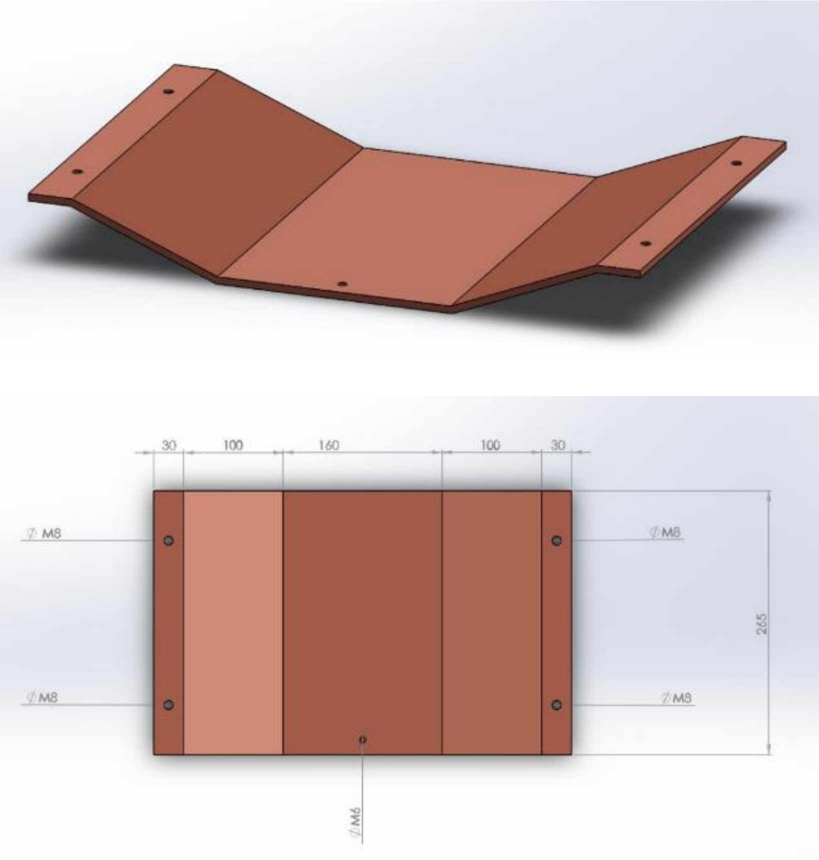


Figure 6. Earth electrode model and dimensions (Knight 2015).

9.1.2 Battery Management System

While a battery management system might not currently be specified by any standards due to the relatively new area of battery electric vehicles, “[it] is a key element to make the utilization of the battery in the smart grid and EVs [electric vehicles] safe, reliable and efficient.” (Rahimi-Eichi et al. 2013) A BMS is useful in the application of battery driven electric vehicles as they serve to control the operational conditions of the battery in order to increase the lifetime of the battery cells while also guaranteeing safety (Rahimi-Eichi et al. 2013).

In order to explain how the BMS operates within the REVSki, it is important to first introduce the models used as the functionality of BMS models can vary between manufacturers. The setup used within the REVSki is a ZEVA Battery Management Master Control Unit (BMMCU) V1.0 alongside four ZEVA BMM8 V1.5. The BMMCU can be seen in Figure 7 while the BMM8 modules can be viewed in Figure 8. It is important to note that ZEVA has updated the firmware of our v1.5 modules to that of v1.6, allowing the v1.6 manual to be followed. The v1.6 manual can be found in full if desired in Appendix A.

Figure 7. ZEVA BMMCU v1.0 (ZEVA 2017).

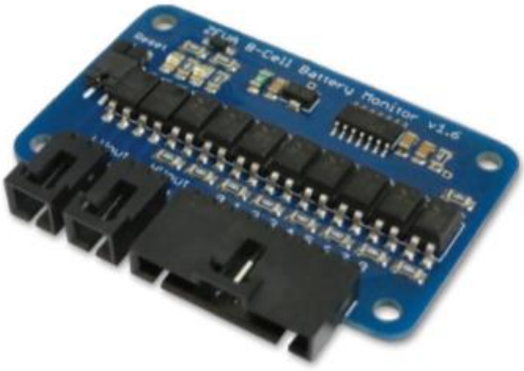


Figure 8. ZEVA BMM8 V1.6 (ZEVA 2017). N.B. REVSki BMM8 firmware has been updated to v1.6.

The BMM8 modules are units that monitor the voltage level within the battery pack it is wired to. A single BMM8 is capable of monitoring two to eight battery cells in series and is capable of taking action if any of the cells contain a voltage out of range (ZEVA 2017). The specifications of the BMM8 can be seen below in Table 1.

Table 1. ZEVA BMM8 Specifications. (ZEVA 2017)

Cell Capability	2-8 cells
Over-voltage Threshold	3.8V
Under-Voltage Threshold	2.5V
Sampling Rate	10 Hz
Dimensions	60x37x5 mm
Power Consumption	8.5 mA

The reasoning behind the use of a monitoring system used on the cells is due to the manufacturing tolerance between all battery cells. All batteries have a slight variation in capacity and as such vary in speed in order to achieve a full charge or to reach a full discharge (ZEVA 2017). By keeping the limits between 2.5V and 3.8V, the life of the batteries is prolonged as they will not be discharged too low and, in doing so, be damaged.

As for the operation itself, the BMM8 effectively operates as a relay switch, when reading the cell's voltages between the appropriate limits, the switch closes, allowing a signal to flow through to the desired power switches (ZEVA 2017). The recommended wiring installation, as supplied by ZEVA (2017), can be seen in Figure 9 below.

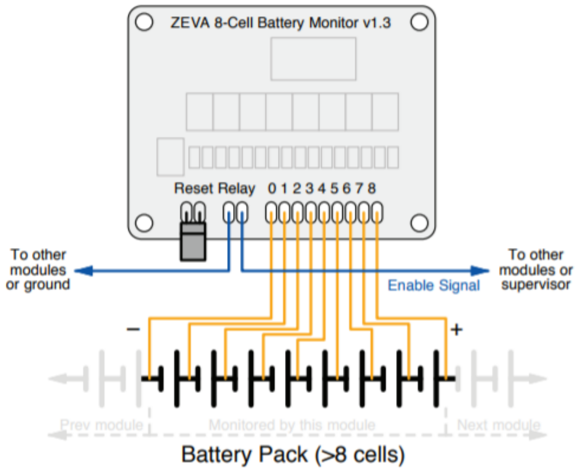


Figure 9. Recommended wiring diagram for a ZEVA BMM8 V1.5 (ZEVA 2017).

As the REVSki consists of a 30 series battery pack, four BMM8 modules have been implemented as they can be cascaded to accommodate the larger number of cells. The wiring of the entire BMS system will be discussed in detail in *Section 10 – Process*.

The ZEVA BMMCU is the unit that will receive the signal input from the BMM8 modules and will either cut power or charging accordingly. The connections of the BMMCU have been listed in Table 2 following and can be easily seen in Figure 10.

Table 2. ZEVA BMMCU Connection list (ZEVA 2017).

LVI	Low Voltage Input	Signal from battery cells
HVI	High Voltage Input	Signal from battery cells
RST	Reset Switch	Momentary switch to reset MCU
DVE	Drive Output	Pull-down on drive contactor
CHG	Charge Output	Pull-down on charger relay
BUZ	Warning Buzzer	12V warning buzzer
GND	Chassis Ground	
12V	12V Supply	

The recommended wiring diagram for the BMMCU can be seen in Figure 10 below.

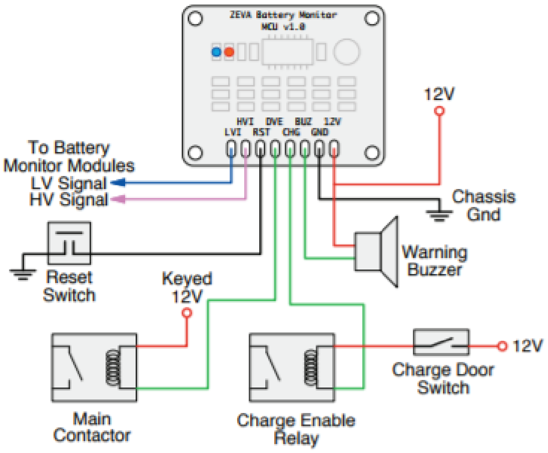


Figure 10. Recommended wiring diagram of the ZEVA BMMCU V1.0 (ZEVA 2017).

The intended operation of the BMMCU is that the main contactor controls the main drive function, in the case of the REVSki this means it must cut the power of the 96V DC line. The charge enable relay, as the name suggests, must be capable of allowing the charger to operate or shut down. When the battery cells are within the appropriate ranges, the relays will close, allowing a signal to reach the LVI and HVI inputs of the BMMCU, which will then supply an output from the DVE and CHG outputs, closing any relays they may be connected to, allowing the REVSki to operate in water or charge if out of the water.

The benefit of the BMS is that of extending the lifetime of the battery cells, through preventing the capability of discharging below the threshold recommended by the battery manufacturers. As stated by Headway (n.d.), the cut-off discharge voltage is 2V which is 0.5V lower than the low voltage threshold determined by the ZEVA BMM8 V1.5. This battery protection also happens to double as protection for the user, preventing overcharge of the battery cells. When a lithium ion battery is overcharged, the additional energy greatly increases the potential for thermal runaway which also has the potential to cause a fire if any flammable materials or gases are exposed to this high temperature environment (Wu et al. 2015).

9.1.3 Design of Systems within the REVSki

In the design phase of the Battery Management System and the wiring integration of the Insulation Monitoring Device, it was important to keep many factors at the forefront of design considerations. These factors included; satisfying any relevant standards, for example the waterproofing of the electrical components, the robustness of components, the ability to bypass systems if undesirable side effects occurred and the ease at which one is able to access all components within the REVSki, either for removal, replacement or general maintenance.

9.1.3.1 Ease of Access and Disassembly

At the beginning of the project for 2017, one of the tasks undertaken by another team member was to adjust the inside configuration of the REVSki for better stability. In order to complete this, the first step was to disassemble all components of the REVSki bar the motor. Whilst performing this task, it came to the team's attention the impracticality of the assembly. For example, many of the components being soldered together in hard to reach locations rather than implementing a simpler solution of connectors. Another example showed the lack of foresight for removal, implementing 12 inch bolts which required the team to reach into the REVSki and attempt the undo the nut located at the base of that 12 inch bolt. This lack of consideration for future maintenance significantly impacts efficiency when works are to be completed on the REVSki.

In order to increase the efficiency and reduce the complexity of the inner components of the REVSki, the team decided to utilise a modular architecture (Golfmann & Lammers 2015). This allows not only easier disassembly, but allows for easier reconfiguration if future work on the project is deemed necessary. This change in design architecture was implemented in the form of ring or spade crimp connectors and circular connectors. This change meant that if a team member wishes to remove a component, they are able to simply unplug it from the system, once the system has been isolated from the power source. Examples of the crimp connectors and circular connectors can be seen in Figure 11.

Figure 11. From Left to Right - Ring Crimp Connector (Oz Auto Electrics 2017), Spade Crimp Connector (Alibaba 2017) and Circular Connector (Altronics 2017).

One of the other changes was the use of nuts and bolts, as many of the nuts and bolts were previously in extremely difficult to reach places, tapped threads were implemented and if they were not possible, access to the nuts and bolts were made easier by location adjustments.

9.1.3.2 Waterproofing

One of the issues that must be considered with a modular design is that it may affect the watertightness of the electrical components, therefore, it was critical that any adjustments made satisfied the condition of an IP 55 or above rating as specified by the Australian standard; AS/NZS 3004.2-2014 Clause 7.3.2. To exceed this requirement, the team aimed for a minimum IP rating for any components to be IP 65 or above. From the Australian Standard AS 60529-2004 this means that the components will be completely dust-tight, completely reducing the possibility of dust ingress. It also means that the components will be protected from jets of water from any direction without harmful effects. Components within the REVSki that possess this level of IP rating include; all enclosures, glands for wire connections between enclosures and circular connectors. The 5-pin connector shown in Figure 11 is one of many used within the REVSki and is rated IP 66 (Altronics 2017).

9.1.3.3 Relay vs. Microcontroller

As the safety system requires a signal to cut power or charging when certain conditions occur, a smaller component is required that is capable of acting as the switch. There are two parts with this ability; a relay switch and a microcontroller. According to Riley White’s thesis on Safety systems (2013), lessons learned from previous REV projects have shown that relay switches are more reliable than microcontrollers. This potentially could be caused by coding errors, however, for the simple use of receiving a signal in one and switching another, a relay is preferred for their simplicity and robustness. No programming is required, reducing the risk of failure from implementation. Based off of REV project history, relays will be used where possible.

9.1.3.4 Latching/Charging Bypass and Start-up Circuit

As previously mentioned, the ZEVA BMMCU receives a low voltage input and a high voltage input, where the low voltage input controls the drive output and the high voltage input controls the charge output. With the current setup, the LVI and HVI are wired in parallel, meaning that whether the BMM8 units are overcharged or overdischarged, both outputs will be disabled at once. While simple in design this poses the issue that, when run to an overdischarged condition, the charger will not be able to operate as the charge output will be shut off. In order to get around this a latching circuit has been designed. This circuit is wired in a way that can bypass the BMS when a momentary button is held down by a user. For example, if the batteries are flat and the BMS is preventing charging, a user holds this button for the first 10 seconds, allowing the charger to switch on. Once the 10 seconds is over, the batteries will be above the low voltage threshold and will charge as per usual. The added benefit of this circuit is that it requires the user to push the momentary button whenever charging is desired, this prevents the charger from switching on and off constantly once it reaches the full charge state. The wiring for the latching circuit can be seen in Figure 12 below.

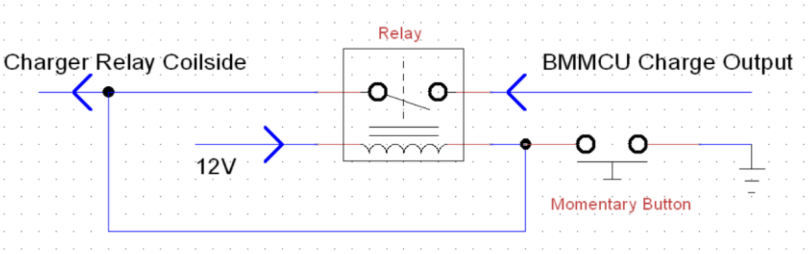


Figure 12. Latching/Charging Bypass Circuit Wiring Diagram

9.1.4 Expected Benefits

The expected benefits of correctly installing the Insulation Monitoring Device and Battery Management Systems mainly targets safety, for the components themselves but more importantly, for the user on the REVSki. The Battery Management System also has the added benefit of cost reduction, by restricting battery operation to within safe operating limits the possibility of battery damage by overdischarging is eliminated, which will increase the time between battery replacements for the user, highly desirable considering the present markets $LiFePO_4$ cell prices. Alternatively, this safety and cost benefit is achieved at the expense of runtime; by limiting the battery operating limits, this also reduces the amount of time a user is able to spend on the REVSki, although justified.

10 PROCESS

10.1 CONSTRAINTS

The two major constraints that influenced the design of the safety system were cost and a dimensional constraint. While the REVSki received sponsorship from many local companies, the aim of the REVSki was not solely a proof of concept but an economically viable proof of concept. Therefore any decisions made for the design were to be as cost effective as possible, whether that meant reducing the number of components where possible or effective procurement. The second constraint was due to the space available inside the hull of the REVSki. With the majority of space being occupied by the major components; including the batteries, motor, motor controller and fuse box, any additional designs were to be as space efficient as possible. This was due not only to be fitted into the REVSki but to allow space for maintenance of other components without reducing work efficiency.

10.2 WIRING AND INSTALLATION

10.2.1 Previous Wiring and Configuration

The previous configuration of the REVSki had the battery cells sealed in PVC tubes in a configuration of 2x7-cell tubes and 2x8-cell tubes. An example of a 7-cell battery pack and its tubing can be seen in Figure 13. The design had the major electrical components such as the motor controller and fuse boxes positioned on a plate over the electric motor toward the stern of the REVSki, the four battery packs were positioned towards the bow of the REVSki, beneath the steering and front access hatch. The position of the battery packs so far forward resulted in an extremely front heavy loading. A model that shows the previous and current configuration that has been created by a fellow REVSki member, Rain Yu Liu, can be seen in Figure 14. The green line represents the approximate centre of mass of an ICE Jet-Ski while the red lines represent the approximate centre of mass of each configuration for the REVSki, with the previous configuration being much closer to the bow than the proposed configuration.

Figure 13. 7-cell Battery Pack and PVC Tubing.

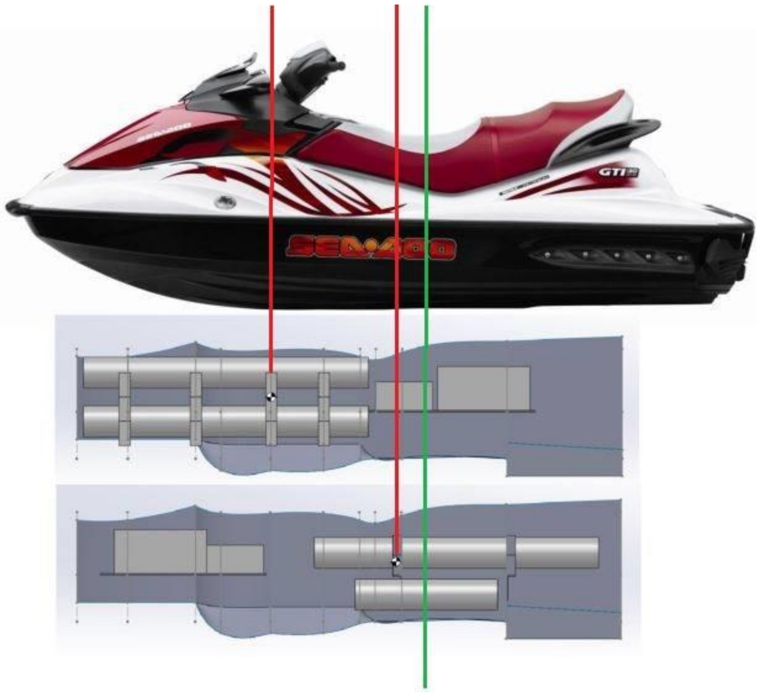
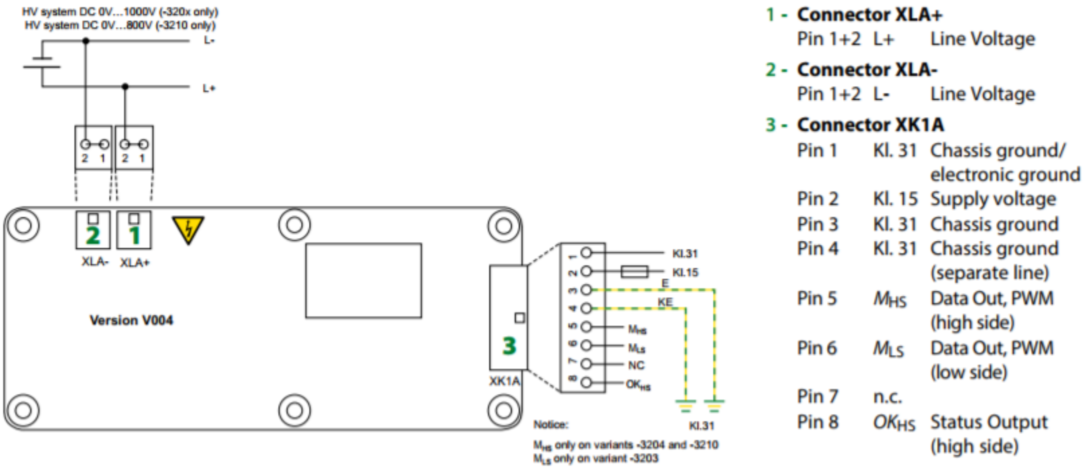


Figure 14. From Above - The Sea-Doo GTI 130 used, the previous configuration and the present configuration (Yu Liu 2017).

The previous design positioned the ZEVA BMM8 modules for each battery pack sealed within the pack, inside the tube caps, which can be easily viewed in Figure 15. While the BMS modules were sealed away, the 2017 team found that the wiring outside of each individual battery pack was not connected, nor was the ZEVA BMMCU module installed anywhere on the REVSki. In other words, construction of the BMS had only begun in its initial stages when the previous team had completed their projects.

The issue with the previous location of the BMS was that of accessibility. The BMM8 modules possess LED lights which blink at 1Hz when undercharged and flash at 2Hz when overcharged (ZEVA 2017). By sealing the BMM8 modules inside the battery tubes, a user is unable to determine which batteries possess issues by a fast visual reference, compounding this, any maintenance on the BMS would require a complete disassembly of the REVSki, an extremely inefficient use of maintenance time.

The Bender IMD was previously connected correctly as per the suggested wiring diagram shown in Figure 15. All connections are wired as suggested except Pin 5 & 6, as a data out connection is not required for the planned use of the IMD. The concern of the Bender wiring, however, was that as no other components of the safety system were implemented along with the IMD, a modification to the existing wiring would be required to ensure that the IMD and BMS would operate within a daisy chain configuration. This means that the system requires both the IMD and BMS to be operating within safe limits for the drive or charge relays to close. The wiring adjustments will be discussed in the following section.



1 - Connector XLA+

Pin 1+2	L+	Line Voltage

2 - Connector XLA-

Pin 1+2	L-	Line Voltage

3 - Connector XK1A

Pin 1	Kl. 31	Chassis ground/ electronic ground
Pin 2	Kl. 15	Supply voltage
Pin 3	Kl. 31	Chassis ground
Pin 4	Kl. 31	Chassis ground (separate line)
Pin 5	M_{HS}	Data Out, PWM (high side)
Pin 6	M_{LS}	Data Out, PWM (low side)
Pin 7	n.c.	
Pin 8	OK_{HS}	Status Output (high side)

Figure 15. Bender IR155-3204 IMD Recommended wiring diagram (Bender 2016).

10.2.2 Current Wiring and Configuration

The objective for this year with regards to the safety system was to ensure that the BMS system was completely wired up and integrated with the Bender IMD to act as the REVSki safety system. The basic visual aide showing the architecture of the proposed design can be seen in Figure 16. Due to the second 2017 objective, the configuration of the battery cells changed from the previously mentioned 2x7 and 2x8 cell setup into a 3x8-cell and 2x3-cell setup. Due to now essentially containing 5 battery packs, a challenge that needed to be overcome was how to complete the BMS whilst only using the 4 BMM8 modules that were purchased prior to 2017.

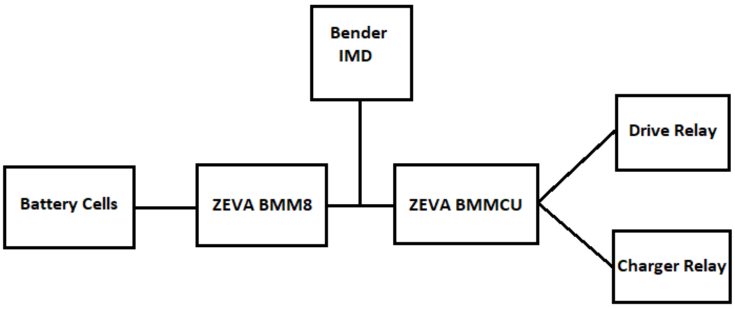


Figure 16. Basic Block Diagram of Proposed Design.

10.2.2.1 BMS Configuration

The first target was to increase the ease of access to the BMM8 modules and in doing so, increasing the efficiency of maintenance. In order to achieve this, the modular design mentioned in *Section 9.1.3.1* was implemented, creating a ‘BMS Enclosure’ that would be positioned in an easier to access location. The BMS enclosure contains all four of the BMM8 modules, the BMMCU module and the appropriate relays to integrate the BMS and IMD into a complete safety system as well as to operate as a latching and bypass circuit if required. The wiring diagrams and explanation of the circuitry will be covered in *Section 10.2.2.4.*

The second target was to solve the issue of how to make use of the four BMM8 modules to monitor the five individual battery packs. As the number of cells in series is identical, the purchase of another BMM8 unit was not required and fortunately, the modularity design allowed for an easier solution. The three 8-cell tubes were each designated their own BMM8 unit for monitoring while the two 3-cell tubes were to share a single unit between them. Configuring the setup in this way, however, results in some rules that must be followed when assembling the REVSki. The first is that the BMM8 units must be wired up in series from the 0 pin being the most negative cell up to a possibility of 8, which must contain the highest potential. This means that the two 3-cell battery packs must always be wired in series in the same order, after every disassembly and reassembly, to ensure that none of the battery cells would be short-circuited when plugged in to the BMM8 unit. To overcome this issue, the team has designated each battery tubing with a naming convention and diagram that is to be followed at all times. The battery configuration with the naming convention can be seen in Figure 17. The second issue is that the pin designated as Pin 8 on the BMM8 is the powered pin and, if any number of cells less than 8 are used, then Pin 8 must be shorted to the next highest used, which in the case of the two 3-cell batteries is Pin 6. This was completed simply by soldering a wire between the two pins.

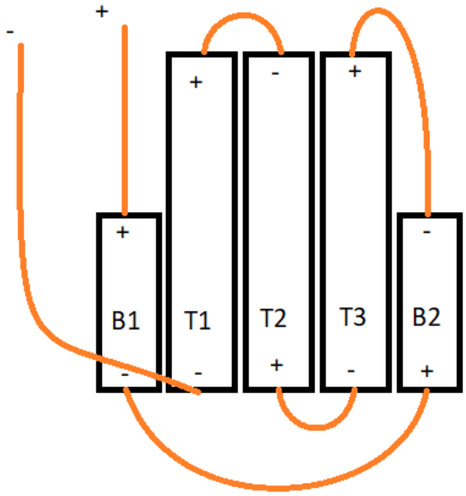


Figure 17. Battery Configuration. N.B. Order of T1, 2 & 3 are not critical.

10.2.2.2 Resettable Fuses

In order to protect the BMS modules monitoring the battery cells from the potential of any short-circuit, fuses must be used. ZEVA suggests that to protect the BMM8 units, if an inline fuse is not used, a wire gauge of approximately AWG 26 should be used (ZEVA 2017). A wire gauge of AWG 26 approximates to a maximum amp rating as 2.2A (PowerStream 2017). As the batteries would be sealed, it is undesirable to be required to disassemble the REVSki to replace any burnt out wiring if short-circuits were to occur. Keeping this in mind, the team chose to implement inline fuses. The next step was to make the informed decision of whether to use a non-resettable fuse or a resettable fuse, formally known as a Positive Temperature Coefficient (PTC) resettable fuse. Following the same logic that led to the decision of using fuses, it is not convenient for a team member to have to disassemble the REVSki to replace a fuse, a PTC fuse is much more convenient as it is capable of resetting on its own if the short-circuit is removed. On the chance that the short-circuit is found within a battery pack, a disassembly will be required anyway, however, with the resettable fuses this is kept as the last resort. The PTC fuses used within the REVSki can be viewed in Figure 18. The team also has a method of determining which particular cells possess a short-circuit; a voltmeter apparatus consisting of 8 voltmeters (one for each cell within a battery pack) was created by a 2017 REVSki team member, Maximilian Jacob. The apparatus will be described in detail in the following section.

Figure 18. PTC Resettable Fuses used within each battery pack (Altronics 2017).

10.2.2.3 Voltmeter Apparatus

While the REVSki would have a way to monitor the individual cell voltages and operate accordingly, the team required some way of being able to read and record these readings. Jacob created this test apparatus that is capable of showing the voltage readings of every cell within an individual battery pack. With the modular design focus of the BMS, the connectors that run from all battery packs to the centralised BMS enclosure can be disconnected and connected to this apparatus, which will display the voltage readings. If any cells do not show a reading, then it can be asserted that a short-circuit exists between that line and elsewhere. The voltmeter apparatus can be seen in Figure 19. As can be seen, there are three connectors for the varying types of connectors running from the battery packs. All 8-cell batteries use the same 9-pin connector as they can be interchangeable, the two 3-cells must be in a specific order and, in an effort to prevent the possibility of an incorrect connection and subsequent short-circuit, use a 5-pin and 6-pin connector respectively. The wiring diagram of the voltmeter apparatus can be viewed in Appendix B.

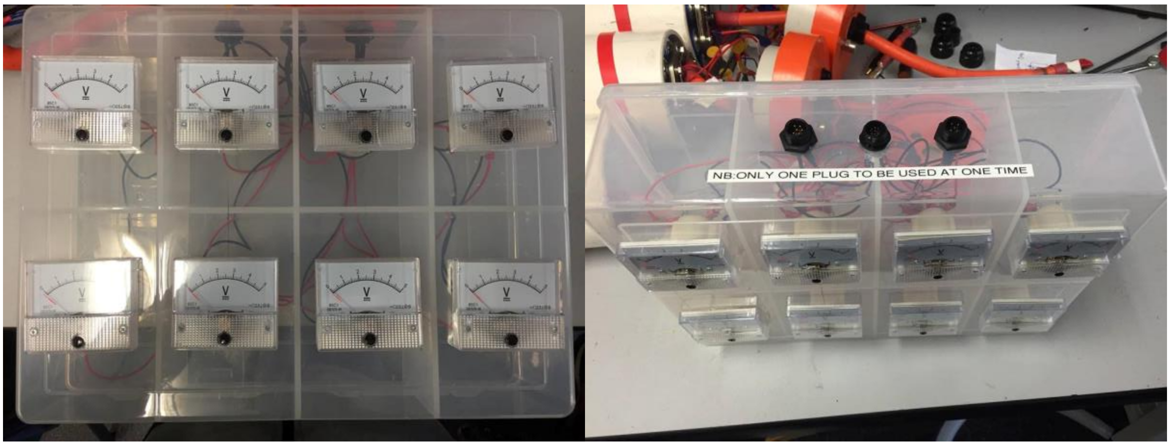


Figure 19. Voltmeter apparatus showing the 8 individual voltmeters (left) and the connector plugs (right).

10.2.2.4 Planned Wiring

In order to best explain the wiring that has been implemented in the REVSki, a diagram of the wiring will be shown of both the entire REVSki circuit and the safety system in separate diagrams. First, the REVSki circuit can be seen in Figure 20. What should be focussed on in Figure 20 is the central dotted box containing the 'Safety System.' The outputs and inputs of this 'Safety System' correspond with the inputs and outputs of the ZEVA BMMCU. This is because the team desired the components within the safety system to be self-contained, with the BMMCU controlling all signalling to and from the safety system, allowing control of the drive and charge relays. To aid in understanding how the 'Safety System' operates, the scenario of the battery cells within safe operating limits should be considered. In this situation and once the DC-DC converter supplies a 12V and ground supply, the drive and charger signals are output as ground; on the charger side, this allows the double relay to switch closed, and if the charger is plugged in, supplies a ground signal to the charger, allowing the charger to switch on and operate. On the driver side, as long as the ignition switch is turned on and the deadman switch plugged into the REVSki, the 'Key Switch Relay' will close, allowing power to flow to the Key Switch Input of the motor controller. The motor controller then allows a signal to power the main 'Contactor A,' allowing the REVSki to operate.

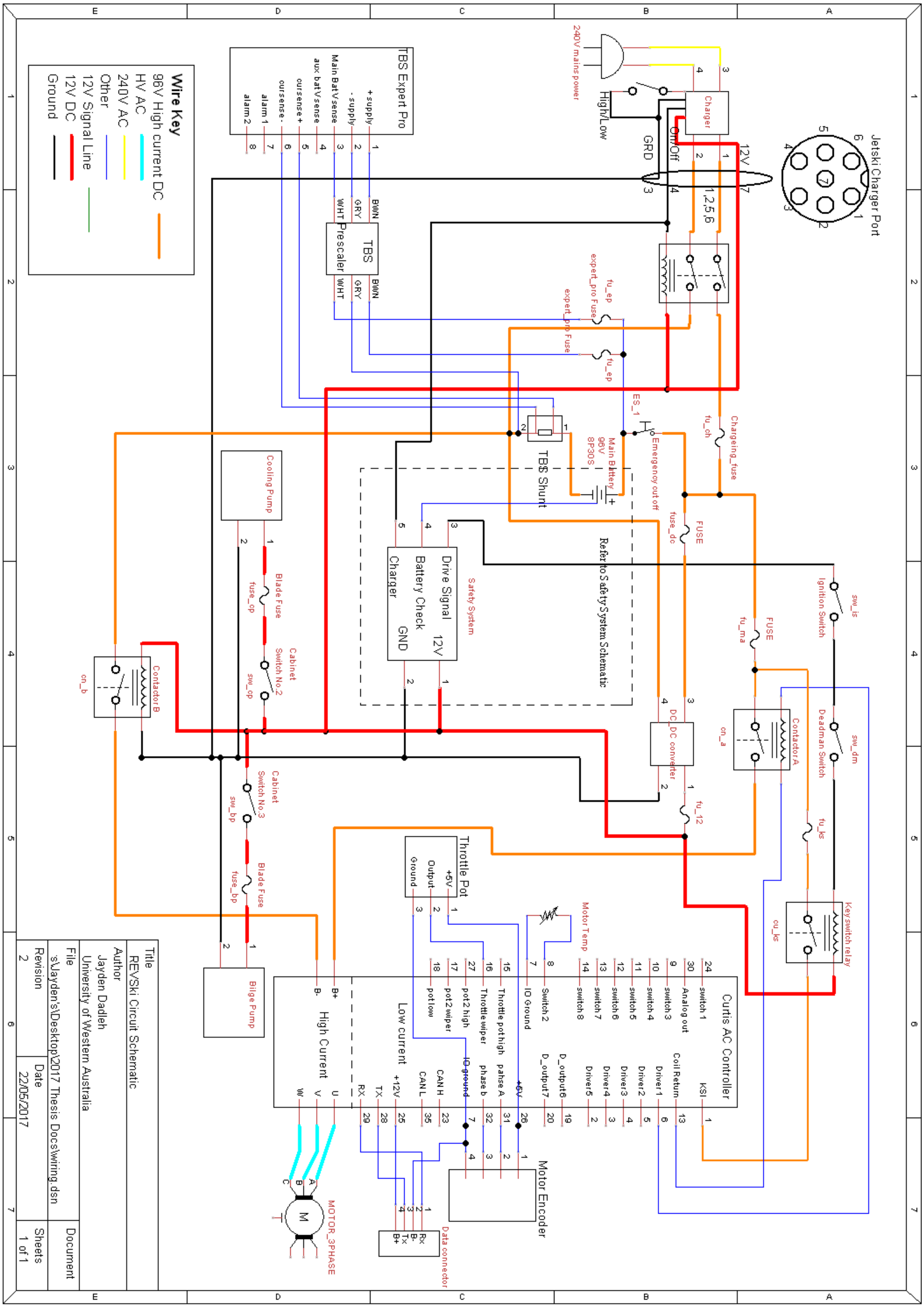


Figure 20. REVSki Electrical Schematic (Dadleh 2017).

The safety system wiring diagram, as can be seen in Figure 21, shows all of the wiring from the signal lines of the battery packs, until the input and output lines which could be seen leaving the 'Safety System' box found in Figure 20. The safety system diagram can be broken up into five smaller components including;

- Battery cells and their fuses
- BMM8 modules
- BMMCU module
- Bender IMD module
- Charger bypass and start-up circuit

To explain how the components work together; when all battery cells are operating within limits, their relay switch closes, allowing a ground signal to input to the BMMCU. In order to integrate the BMS and IMD together, the team has wired this BMMCU input line to a relay switch that is powered by the IMD. From Figure 15 it is known that Pin 8 from the IMD is the OK signal and according to the Bender IR155-3204 manual (2017), the output signal when within range is 2V. Hence, for the BMMCU to receive any ground signal input, it requires not only the BMM8 units to close their switches, it also requires that the IMD sends an OK signal that can close the relay switch. The Bender IR155-3204 manual can be found in Appendix C. The charger bypass circuit was previously explained in *Section 9.1.3.4.*

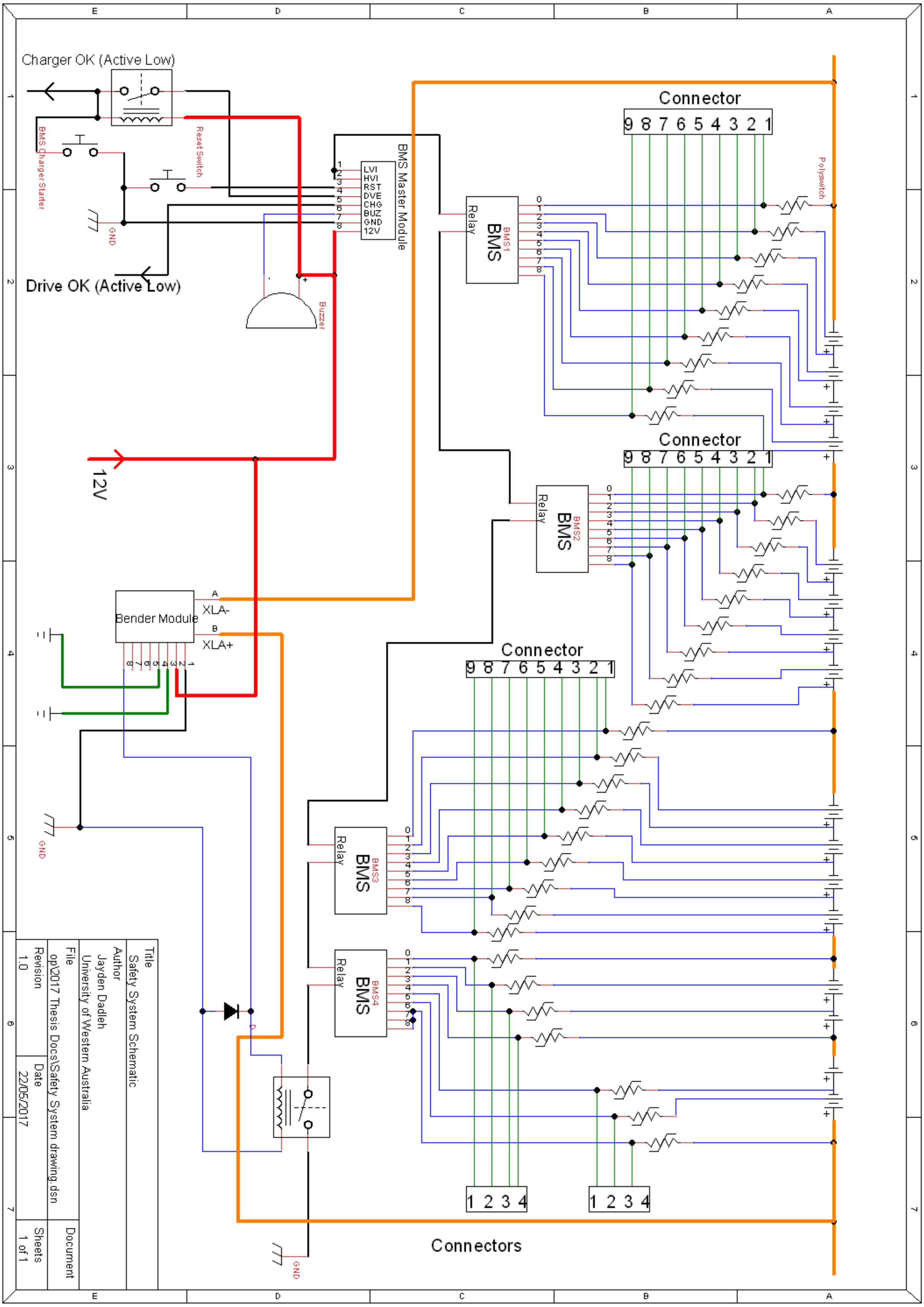


Figure 21. Safety System Wiring Diagram (Dadleh 2017).

10.2.2.5 Enclosure and Implementation

The final component of the current REVSki safety system is the BMS enclosure itself. As defined by AS/NZS 3004.2-2014 Clause 7.3.2, the minimum IP rating is at IP 55, however, as mentioned in *Section 9.1.3.2* the team had decided to attain a rating of IP 65 or above. As the safety system is vital to both the components and the user, it is important that the risk of water ingress is minimised to the fullest degree. This resulted in the team purchasing an IP 65 rated enclosure which can be seen in Figure 22, along with the safety system. It is important to note that the IMD is within its original enclosure as seen in Figure 5, the only modification required was to alter the OK signal output to lead to the BMS enclosure, then wired as per Figure 21.

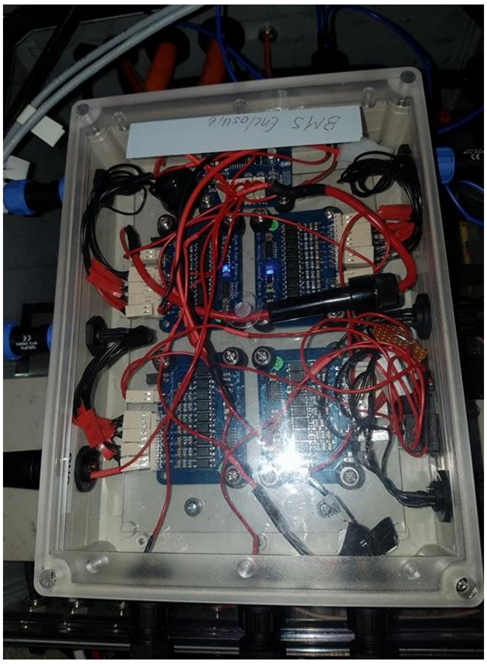


Figure 22. BMS Enclosure.

10.3 TESTING

The final objective of this component of the REVSki project was to test the operation of the safety system. The BMS will be the sole focus of the testing as it is an almost completely new installation. The primary aim of the BMS testing was to ensure that it operates as is specified by the manual, cutting off operation at 3.8V for over-charge and 2.5V for under-voltage.

This testing was achieved through a charge and discharge cycle, the voltmeter apparatus would be used in conjunction with the BMS system to record the voltage levels of every cell both before charge and after charge. This voltmeter apparatus and cyclic testing also has the added benefit of monitoring the voltage drift within the batteries, where after a number of cycles, a trend could be determined if present and a qualitative analysis of the battery capacity and quality could be conducted. Any batteries that behave undesirably for the REVSki operation would be detected by the voltmeter apparatus and action can be taken accordingly.

11 RESULTS

Following the completion of the REVSki, the testing could take place for all aspects, including the BMS system, stability and general wiring changes, as any fault could occur. For the BMS system, a charge was required under supervision to ensure that the over-voltage threshold operated as required. Once charging was completed, signified by the BMS cutting the signal line to the charger and subsequently stopping charging, the first voltage recording took place. This recording can be seen in Table 3.

Table 3. Initial Voltage Recording following first charge.

All in (V)	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8
T1	3.3	3.3	3.4	3.3	3.3	3.2	3.3	3.3
T2	3.3	3.3	3.4	3.3	3.3	3.2	3.3	3.3
T3	3.3	3.3	3.3	3.3	3.3	3.2	3.3	3.3
B1	3.3	3.2	3.3					
B2	3.3	3.3	3.3					

An issue arose during the water testing of the REVSki, the BMS would consistently drop out after a short period of time, approximately 40 seconds of full throttle then slowly decreasing in time until it cut out after 3 seconds of ~10% throttle. The REVSki was then returned to the lab where the discharge voltage recordings could take place. The second set of recordings can be seen below in Table 4.

Table 4. Voltage recordings following the first complete discharge.

All in (V)	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8
T1	3.1	2.8	3.1	3.0	3.1	2.9	3.1	2.9
T2	3.0	2.9	3.0	3.0	3.1	2.9	2.1	3.1
T3	3.0	2.7	1.8	2.9	3.0	2.9	3.1	3.1
B1	3.2	2.9	2.8					
B2	3.0	2.7	3.0					

As the funding of the REVSki project is a large constraint, with the expensive battery cells it was impractical to replace all cells following the 2016 hiatus. The team attempted to discover and remove all damaged batteries that had lost capacity over the period of inactivity. Unfortunately, two cells were missed, which can be seen highlighted within Table 4; fortunately, it explained the reason as to why the BMS system seemed to be cutting off prematurely. As the damaged cells, T2-7 and T3-3, no longer had capacity, as soon as the throttle of the REVSki was held down, the voltage of these cells would plummet toward the low-voltage threshold of the BMM8 modules.

The damaged battery cells were consequently replaced and an attempt at charging again for another test cycle began, unfortunately, another issue arose, with the team falsely mistaking the current reading of the battery charger of 0A for meaning that the batteries were charged and the BMS had cut charger input. In reality, it was found that the fuse protecting the REVSki batteries from any short-circuit of the charger was blown; the previous team had not installed a 30A fuse for the 25A input charger, rather, they had installed a 20A fuse. Unfortunately, this prevented any additional cyclic tests from being conducted prior to the hand in date of the final year project report. From the information that had been collected, it could be deducted that the BMS system had operated as required, cutting power for the first charge cycle and cutting power for the water test, regardless of the damaged battery cells tripping it much more often than to be expected. Figures 23 & 24 present a visual representation of Tables 3 & 4 in the form of histograms.

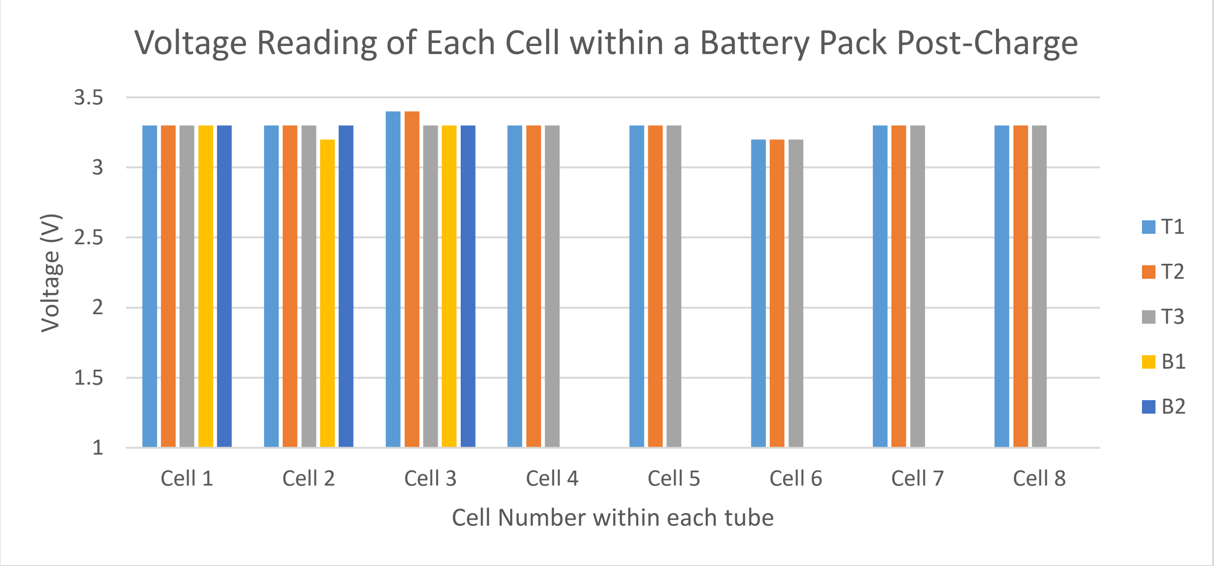


Figure 23. Voltage recording after initial charge.

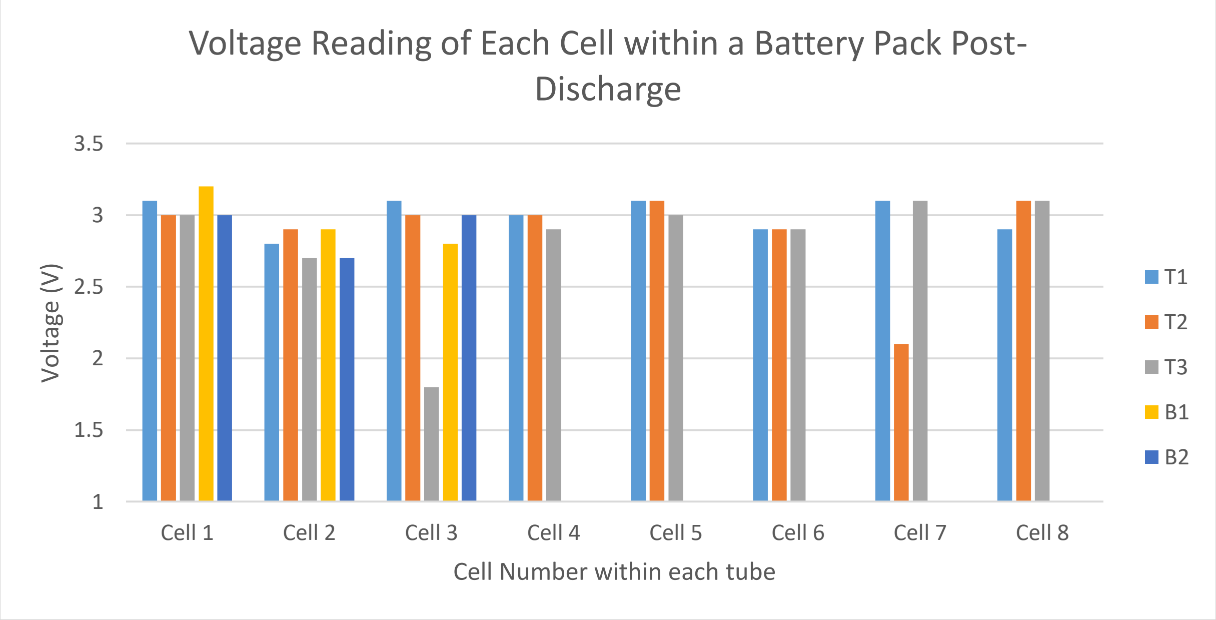


Figure 24. Voltage readings after the first complete discharge.

11.1 INTERPRETATION OF RESULTS

The histograms of Figures 23 & 24 draw attention to the distribution of the voltage levels of each cell before and after the first cycle. It can be noted that after the first charge, the levels of the battery cells are all within a desirable range of each other, with the largest difference at 0.2V. However, after the first complete discharge, the balance of the battery cells seen in Figure 24 are considerably more unruly, with the largest difference, not including the outliers, at 0.5V. This shows that if more funding could be attained, it would be worthwhile to replace all old battery cells as they are damaged to varying degrees. Alternatively, an upgraded

Battery Management System could be considered, one with the capabilities of active cell balancing as well as monitoring, such as the ZEVA BMS12 (ZEVA 2017).

12 CONCLUSION

The REVSki team achieved the goal of implementing an almost brand new BMS and integrating it with a pre-existing IMD to form the foundation of what will be the REVSki Safety System. The team was successful in achieving this by satisfying the relevant standards by waterproofing the enclosures and circuitry. Also, some minor changes were implemented that would make operation much easier for the user, such as the charger start-up/bypass button and modifications of the REVSki including the centralised BMS enclosure and access considerations throughout the design phase.

12.1 FUTURE WORK

Future work on the REVSki is to focus on attaining operability, by obtaining and replacing a new charge fuse that is the appropriate rating for the charger that is used. Once this has been completed, more test cycles can be conducted to monitor the battery cells, the issue with this is that cost is still a major factor for any work with respect to the batteries.

As the main operation of the REVSki is complete, the focus shifts further into the auxiliary systems, mainly that of the REVSki Safety System. With the foundation complete, it is important that the safety system is completed by integrating temperature and water sensor modules. While the temperature sensors and water level sensors have been previously installed, they require a microprocessor to appropriately monitor and react to the temperature readings and water level readings within the battery tubes and REVSki hull respectively. With the completion of the safety system, the REVSki team will be able to present a state of the art project, proving that a cleaner, quieter alternative can be achieved, all with the level of safety that consumers come to expect from the internal combustion engine Jet Skis currently in use.

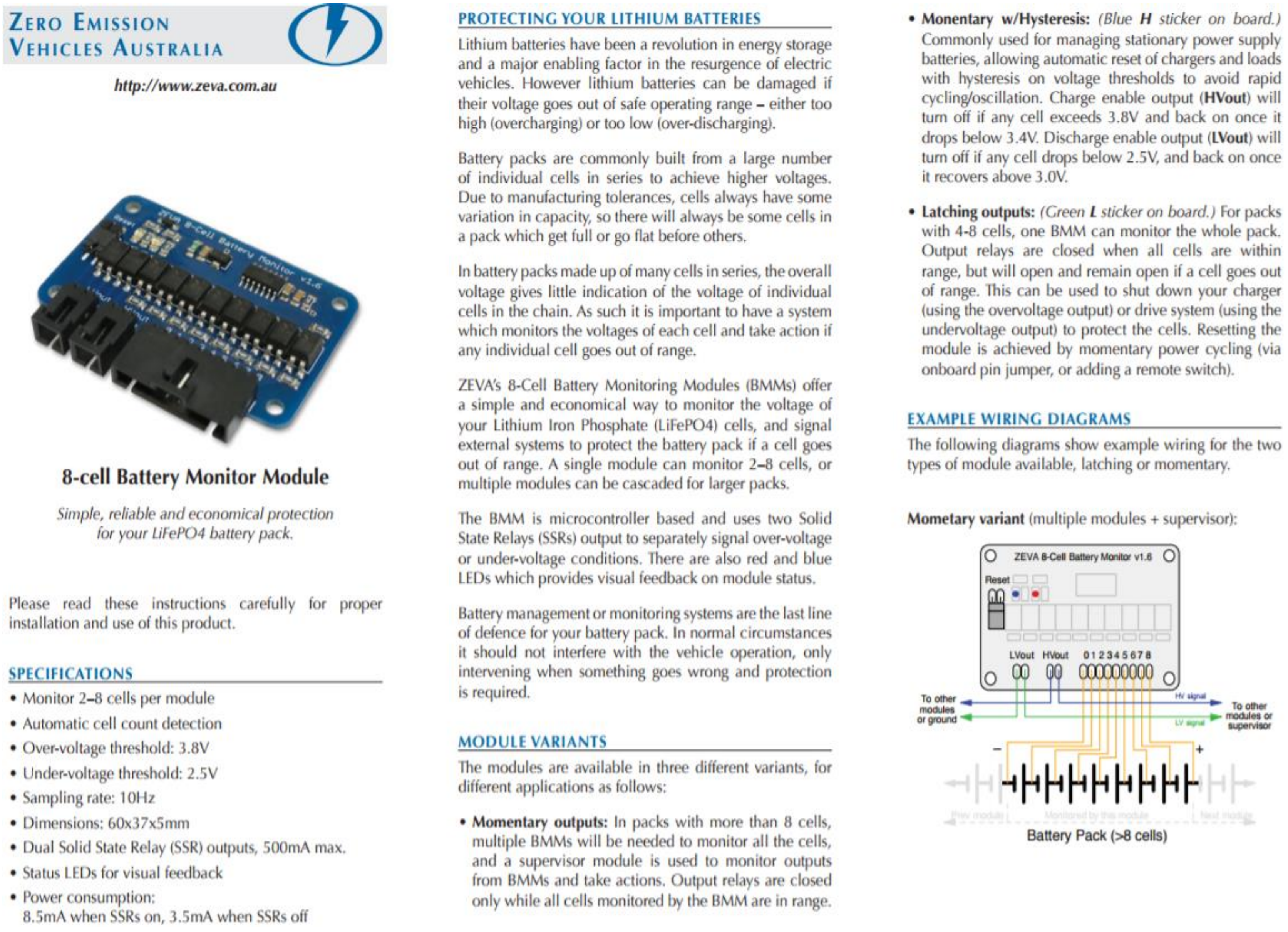
13 REFERENCES

- Australian Government Department of the Environment and Energy n.d., *Tracking Australia's greenhouse gas emissions*. Available from: http://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/tracking-emissions. [30 October 2017].
- Bender 2016, *Isometer IR155-3203/IR155-3204 Insulation monitoring device (IMD) for unearthed DC drive systems (IT systems) in electric vehicles*, manual, Bender. Available from: http://www.bender-es.com/fileadmin/products/doc/IR155-32xx-V004_D00115_D_XXEN.pdf. [30 March 2017].
- Boden, T.A., G. Marland, and R.J. Andres 2017. *Global, Regional, and National Fossil-Fuel CO_2 Emissions,* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy. Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2017. Available from: http://cdiac.ess-dive.lbl.gov/trends/emis/tre_glob_2014.html. [30 October 2017].
- *Global EV Outlook 2017 – Two Million and Counting* 2017, International Energy Agency.
- Golfmann, J. & Lammers, T. 2015, 'Modular product design: reducing complexity, increasing efficacy', EY, vol.7, no.1.
- Headway n.d., *Headway LiFePO4 38120(38105) Specifications*, technical datasheet, Headway. Available from: http://oh8stn.org/wp-content/uploads/2017/09/HeadWay-LiFePO4-38120__-Specifications1-1.pdf. [14 September 2017].
- *National Inventory by Economic Sector 2015* 2017, Australian Government Department of the Environment and Energy.
- PowerStream n.d., *Wire Gauge and Current Limits Including Skin Depth and Strength*. Available from: https://www.powerstream.com/Wire_Size.htm. [22 May 2017].
- Rahimi-Eichi, H., Ojha, U., Baronti, F. & Chow, MY 2013, 'Battery Management System: An Overview of its Application in the Smart Grid and Electric Vehicles', IEEE, vol.7, no.2, pp. 4-16.
- Standards Australia 2004, *Degrees of protection provided by enclosures (IP Code),* AS 60529-2004. Available from: Australian Standards. [4 April 2017].

- Standards Australia 2014, *Electrical Installations – Marinas and boats – Boat installations,* AS/NZS 3004.2-2014. Available from: Australian Standards. [5 June 2017].
- The REV Project 2017, REV Electric Jet Ski, The University of Western Australia. Available from: http://therevproject.com/. [12 April 2017].
- United States Environmental Protection Agency 2017, *Global Greehouse Gas Emissions Data.* Available from: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Trends. [30 October 2017].
- Wu, C., Sun, J., Zhu, CZ., Ge, Y. & Zhao, Y. 2015, 'Research on overcharge and overdischarge effect on lithium-ion batteries', Vehicle Power and Propulsion Conference (VPPC), 2015 IEEE.
- ZEVA n.d., *8-cell Battery Monitor Module,* ZEVA. Available from: http://zeva.com.au/Products/datasheets/BMM8%20v1-6%20Manual.pdf. [15 April 2017].
- ZEVA n.d., *Battery Monitor MCU,* technical datasheet, ZEVA. Available from: https://www.master-instruments.com.au/files/data_sheets/PCM-BMMCU.pdf. [15 April 2017].

14 APPENDIX

14.1 APPENDIX A



ZERO EMISSION VEHICLES AUSTRALIA

http://www.zeva.com.au

8-cell Battery Monitor Module

Simple, reliable and economical protection for your LiFePO4 battery pack.

Please read these instructions carefully for proper installation and use of this product.

SPECIFICATIONS

- Monitor 2–8 cells per module
- Automatic cell count detection
- Over-voltage threshold: 3.8V
- Under-voltage threshold: 2.5V
- Sampling rate: 10Hz
- Dimensions: 60x37x5mm
- Dual Solid State Relay (SSR) outputs, 500mA max.
- Status LEDs for visual feedback
- Power consumption:
  8.5mA when SSRs on, 3.5mA when SSRs off

PROTECTING YOUR LITHIUM BATTERIES

Lithium batteries have been a revolution in energy storage and a major enabling factor in the resurgence of electric vehicles. However lithium batteries can be damaged if their voltage goes out of safe operating range – either too high (overcharging) or too low (over-discharging).

Battery packs are commonly built from a large number of individual cells in series to achieve higher voltages. Due to manufacturing tolerances, cells always have some variation in capacity, so there will always be some cells in a pack which get full or go flat before others.

In battery packs made up of many cells in series, the overall voltage gives little indication of the voltage of individual cells in the chain. As such it is important to have a system which monitors the voltages of each cell and take action if any individual cell goes out of range.

ZEVA's 8-Cell Battery Monitoring Modules (BMMs) offer a simple and economical way to monitor the voltage of your Lithium Iron Phosphate (LiFePO4) cells, and signal external systems to protect the battery pack if a cell goes out of range. A single module can monitor 2–8 cells, or multiple modules can be cascaded for larger packs.

The BMM is microcontroller based and uses two Solid State Relays (SSRs) output to separately signal over-voltage or under-voltage conditions. There are also red and blue LEDs which provides visual feedback on module status.

Battery management or monitoring systems are the last line of defence for your battery pack. In normal circumstances it should not interfere with the vehicle operation, only intervening when something goes wrong and protection is required.

MODULE VARIANTS

The modules are available in three different variants, for different applications as follows:

- **Momentary outputs:** In packs with more than 8 cells, multiple BMMs will be needed to monitor all the cells, and a supervisor module is used to monitor outputs from BMMs and take actions. Output relays are closed only while all cells monitored by the BMM are in range.
- **Monentary w/Hysteresis:** *(Blue **H** sticker on board.)* Commonly used for managing stationary power supply batteries, allowing automatic reset of chargers and loads with hysteresis on voltage thresholds to avoid rapid cycling/oscillation. Charge enable output (**HVout**) will turn off if any cell exceeds 3.8V and back on once it drops below 3.4V. Discharge enable output (**LVout**) will turn off if any cell drops below 2.5V, and back on once it recovers above 3.0V.
- **Latching outputs:** *(Green **L** sticker on board.)* For packs with 4-8 cells, one BMM can monitor the whole pack. Output relays are closed when all cells are within range, but will open and remain open if a cell goes out of range. This can be used to shut down your charger (using the overvoltage output) or drive system (using the undervoltage output) to protect the cells. Resetting the module is achieved by momentary power cycling (via onboard pin jumper, or adding a remote switch).

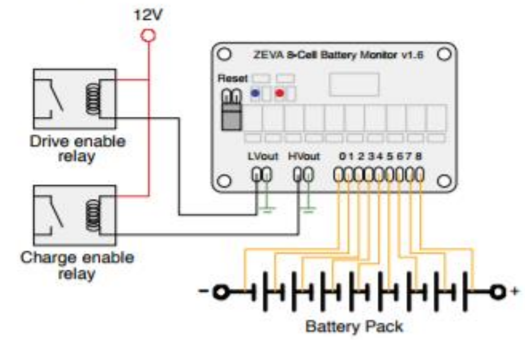
EXAMPLE WIRING DIAGRAMS

The following diagrams show example wiring for the two types of module available, latching or momentary.

Mometary variant (multiple modules + supervisor):

Battery Pack (>8 cells)

Latching or Hysteresis variants (single modules):



In installations with a single "battery enable" relay (combining charge and drive enable function), the **HVout** and **LVout** outputs may be wired in series such that an open circuit on either will open the power relay.

INSTALLATION

Before you commence installation, remove the jumper across the two pins labelled RESET. This will keep the module powered down and offer some protection from temporary wiring faults during installation.

The board has a 3mm hole in each corner which should be used to securely mount the module. If mounting to metal surfaces, use standoffs or an insulating layer between to ensure the circuit board does not contact the metal. Modules should be installed in a location protected from water and debris – typically inside your sealed battery enclosure is ideal.

Once mounted, connect wires from cells to the module plug. We recommend wiring the plug fully before connecting to the module. The BMM uses Molex C-Grid SL locking plugs for connections to cells and outputs. They provide secure, reliable connections, but can be a little fiddly to wire up until you get the hang of it.

The plugs are designed for fairly small gauge wire, around 24-30AWG. The wire's insulation needs to be small enough to fit into the plug housing, which limits outer diameter to about 2mm. The best way to connect wires to pins is crimping first then adding a little solder to the joint. A suitable crimping tool is available from vendors such as Altronics (part T1537).

If you don't have a suitable crimping tool, you can the solder wire directly to the plug, ensuring minimal gap between the insulation and the back of the pin. You may need to compress the wings on the pin insert a little for them to fit comfortably into the housing.

When the pin is fully inserted, a barb on the pin should engage a slot in the housing to lock it in place, and a faint click should be heard. Either inspect visually or give a gentle tug on the wire after insertion to ensure it is secure. Pins can be removed if necessary by applying pressure on the pin's barb with a jeweler's screwdriver, then the pin can be pulled from the housing.

Ensure that all wiring is secured so it will not become damaged from vibration or abrasion.

Power is always taken from input #8. If using the module with fewer than 8 cells, simply add a wire jumper from your top-most cell to input #8. (For example, if monitoring 4 cells add a small wire between input #4 and #8.)

Please consult the manual for your supervisor module or BMS Master Unit for instructions on integrating modules with the rest of your battery protection system.

OPERATION AND USE

Modules will automatically detect the number of cells connected when first powered up, and (if using monentary output variants) will flash the LEDs and outputs according to the number of cells detected for visual confirmation. If the LEDs are blinking alternately, it means zero cells have been detected. Note: *Due to the likelihood of frequent in-system resets, latching variants do not flash outputs on startup. We recommend performing tests after installation to verify all cells are being monitored.*

The threshold for over-voltage is 3.8V, and under-voltage is 2.5V. The blue status LED will be lit whenever the **LVout** relay is closed, and the red LED will be lit whenever the **HVout** relay is closed, i.e both LEDs should be lit whenever all cells are within safe voltage range.

LiFePO4s are typically charged to 3.65V per cell, so if your pack is in a good state of balance the BMMs should not interfere with a normal charge cycle. Once a cell is full, voltage rises quickly and damage may occur above 4.2V, so it is important that your supervisor system can respond by disabling the charger within a few seconds.

When discharging, cells will not suffer damage unless they are driven negative – that is, if a cell goes completely flat (0V) but the voltage from other cells forces current to continue flowing. For the low voltage threshold, 2.5V was chosen because it allows for a significant amount of voltage sag under load (so the BMM will not give false positives during acceleration), but still allowing sufficient notice of a low cell before damage will occur.

POWER CONSUMPTION WARNING

An inherent problem with any BMS which powers itself from the cells it is monitoring is that the BMS itself slowly discharges the cells. In normal operation this effect is insignificant, but if the vehicle is to be left unused for extended periods of time (months or years), it is recommended that either the cells are left fully charged, or the BMMs are powered down (by removing the Reset plug) to ensure they can't flatten any cells.

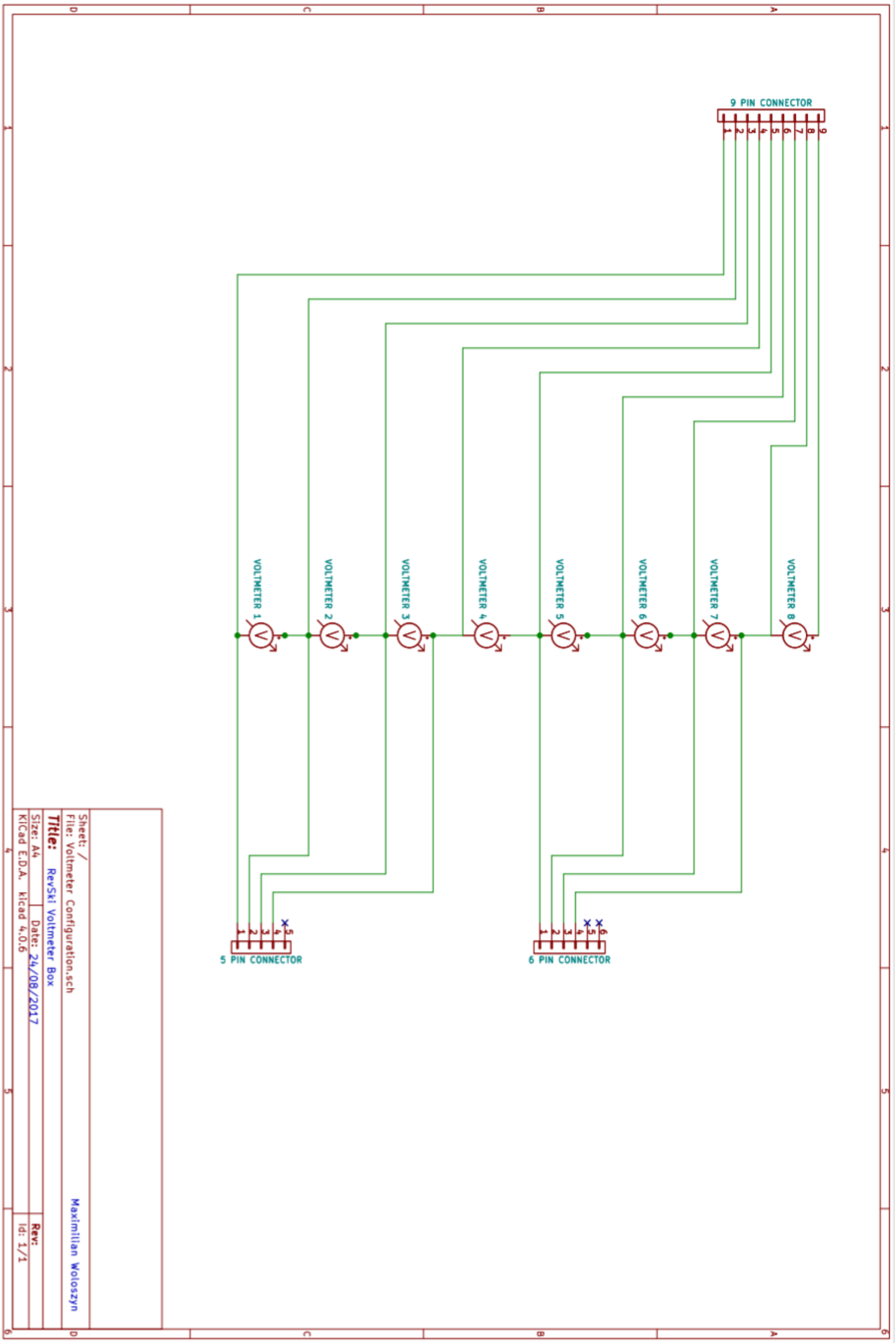
TECHNICAL SUPPORT

If you have any queries not covered by this manual, feel free to contact us via our website: **www.zeva.com.au**

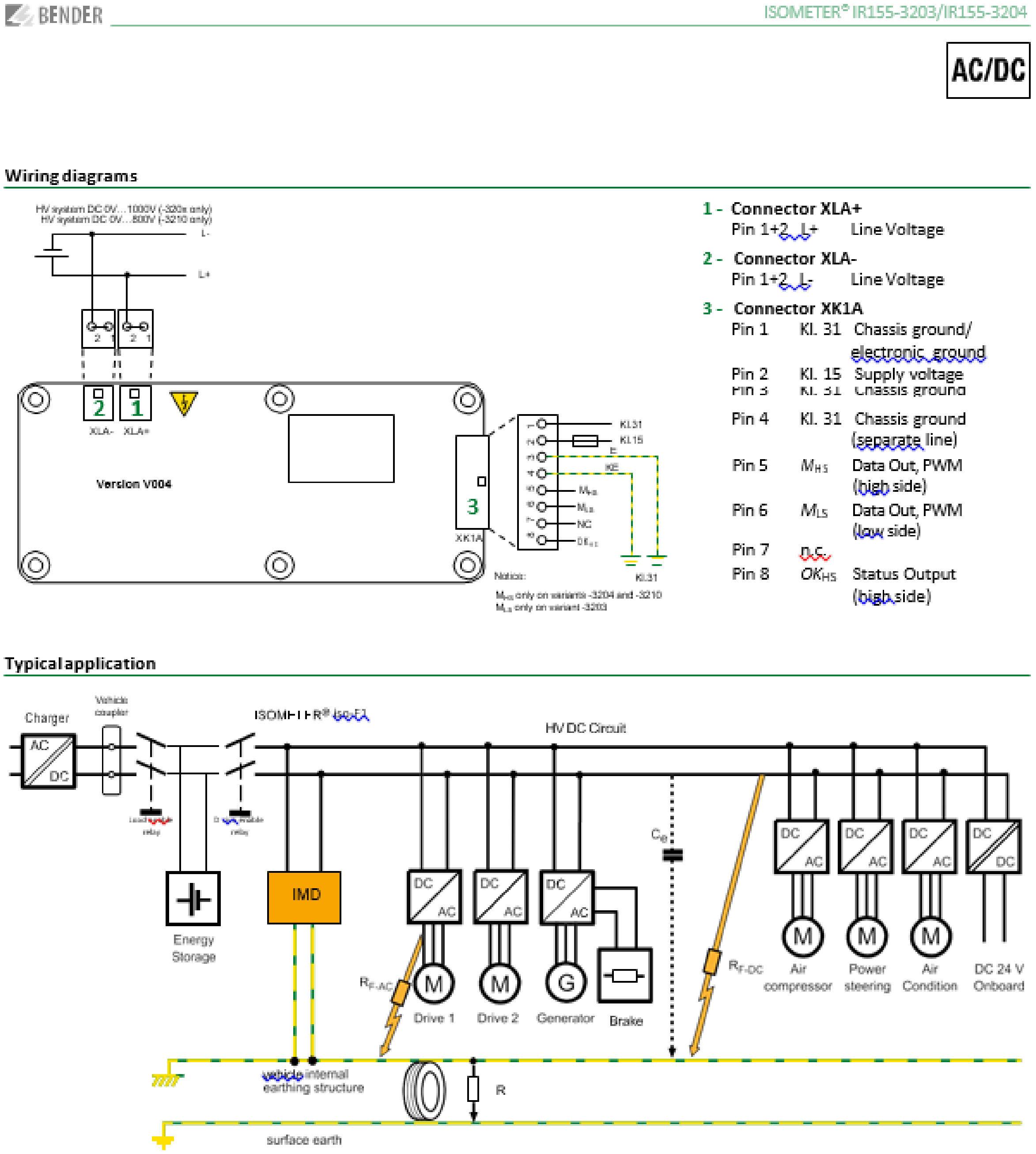
Products are covered against manufacturing faults for a period of 12 months from date of purchase. If you believe your module may be faulty, please contact us for RMA information.

ZEVA is a 100% carbon neutral business. All products proudly designed and manufactured in Australia.

14.2 APPENDIX B



14.3 APPENDIX C



ISOMETER® IR155-3203/IR155-3204

AC/DC

Wiring diagrams

Notice:
M_{HS} only on variants -3204 and -3210
M_{LS} only on variant -3203

1 - Connector XLA+
Pin 1+2 L+ Line Voltage

2 - Connector XLA-
Pin 1+2 L- Line Voltage

3 - Connector XK1A

Pin 1	Kl. 31	Chassis ground/ electronic ground
Pin 2	Kl. 15	Supply voltage
Pin 3	Kl. 31	Chassis ground
Pin 4	Kl. 31	Chassis ground (separate line)
Pin 5	M_{HS}	Data Out, PWM (high side)
Pin 6	M_{LS}	Data Out, PWM (low side)
Pin 7	n.c.	
Pin 8	OK_{HS}	Status Output (high side)

Typical application

Technical data

Insulation coordination acc. to IEC 60664-1

Protective separation (reinforced insulation)	between (L+/L-) – (Kl. 31, Kl. 15, E, KE, M_{HS}, M_{LS}, OK_{HS})
Voltage test	AC 3500 V/1 min

Supply/IT system being monitored

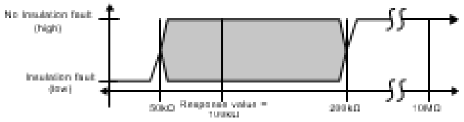
Supply voltage U_S	DC 10…36 V
Max. operating current I_S	150 mA
Max. current I_k	2A 6 A/2 ms inrush current
HV voltage range (L+/L-) U_n	AC 0…1000 V (peak value) 0…660 V r.m.s. (10 Hz…1 kHz) DC 0…1000 V
Power consumption	<2 W

Response values

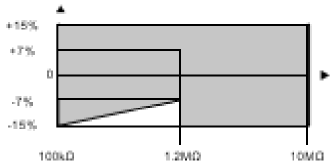
Response value hysteresis (DCP)	25 %
Response value R_{an}	100 kΩ…1 MΩ
Undervoltage detection	0…500 V

Measuring range

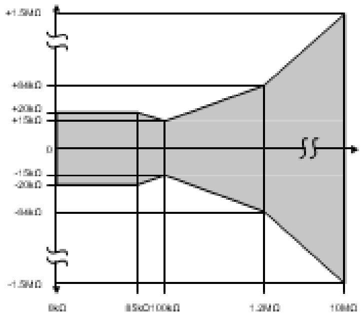
Measuring range	0…10 MΩ
Undervoltage detection	0…500 V default setting: 0 V (inactive)
Relative uncertainty SST (≤ 2 s)	good > 2* R_{an}; bad < 0.5* R_{an}
Relative uncertainty DCP	0…85 kΩ ▸ ±20 kΩ
(default setting 100 kΩ)	100 kΩ…10 MΩ ▸ ±15%
Relative uncertainty output M (fundamental frequency)	±5 % at each frequency (10 Hz; 20 Hz; 30 Hz; 40 Hz; 50 Hz)
Relative uncertainty undervoltage detection	U_n ≥ 100 V ▸ ±10 %; at U_n ≥ 300 V ▸ ±5 %
Relative uncertainty (SST)	"Good condition" ≥ 2* R_{an} "Bad condition" ≤ 0.5* R_{an}



Relative uncertainty DCP	100 kΩ…10 MΩ ±15 % 100 kΩ…1.2 MΩ ▸ ±15 % to ±7 % 1.2 MΩ ▸ ±7 % 1.2…10 MΩ ▸ ±7 % to ±15 % 10 MΩ ▸ ±15 %



Absolute uncertainty	0…85 kΩ ▸ ±20 kΩ



Time response

Response time t_{an} (OK_{HS}; SST)	t_{an} ≤ 2 s (typ. < 1 s at U_n > 100 V)
Response time t_{an} (OK_{HS}; DCP) (when changing over from R_F = 10 MΩ to R_{an}/2; at C_e = 1 µF; U_n = DC 1000 V)	t_{an} ≤ 20 s (at F_{ave} = 10*) t_{an} ≤ 17.5 s (at F_{ave} = 9) t_{an} ≤ 17.5 s (at F_{ave} = 8) t_{an} ≤ 15 s (at F_{ave} = 7) t_{an} ≤ 12.5 s (at F_{ave} = 6) t_{an} ≤ 12.5 s (at F_{ave} = 5) t_{an} ≤ 10 s (at F_{ave} = 4) t_{an} ≤ 7.5 s (at F_{ave} = 3) t_{an} ≤ 7.5 s (at F_{ave} = 2) t_{an} ≤ 5 s (at F_{ave} = 1) during the self test t_{an} + 10 s
Switch-off time t_{ab} (OK_{HS}; DCP) (when changing over from R_F = 10 MΩ to R_{an}/2; at C_e = 1 µF; U_n = DC 1000 V	t_{ab} ≤ 40 s (at F_{ave} = 10) t_{ab} ≤ 40 s (at F_{ave} = 9) t_{ab} ≤ 33 s (at F_{ave} = 8) t_{ab} ≤ 33 s (at F_{ave} = 7) t_{ab} ≤ 33 s (at F_{ave} = 6) t_{ab} ≤ 26 s (at F_{ave} = 5) t_{ab} ≤ 26 s (at F_{ave} = 4) t_{ab} ≤ 26 s (at F_{ave} = 3) t_{ab} ≤ 20 s (at F_{ave} = 2) t_{ab} ≤ 20 s (at F_{ave} = 1) during a self test t_{ab} + 10 s
Duration of the self test	10 s (every five minutes; should be added to t_{an}/t_{ab})

Measuring circuit

System leakage capacitance C_e	≤ 1 µF
Smaller measurement range and increased measuring time at C_e	> 1 µF (e.g. max. range 1 MΩ @ 3 µF, t_{an} = 68 s when changing over from R_F 1 MΩ to R_{an}/2)
Measuring voltage U_M	±40 V
Measuring current I_M at R_F = 0	±33 µA
Impedance Z at 50 Hz	≥ 1.2 MΩ
Internal DC resistance R_i	≥ 1.2 MΩ

* F_{ave} = 10 is recommended for electric and hybrid vehicles

Output

Measurement output (M)

M_{HS} switches to U_S – 2 V (3204)
(external pull-down resistor to Kl. 31 necessary 2.2 kΩ)

M_{LS} switches to Kl. 31 + 2 V (3203)
(external pull-up resistor to Kl. 15 reqired 2.2 kΩ

0 Hz ▸ Hi > short-circuit to U_S+ (Kl. 15); Low > IMD off or short-circuit to Kl. 31

10 Hz ▸ Normal condition
Insulation measurement DCP;
starts two seconds after power on;
First successful insulation measurement at ≤ 17.5 s
PWM active 5…95 %

20 Hz ▸ undervoltage condition
Insulation measurement DCP (continuous measurement);
starts two seconds after power on;
PWM active 5…95 %
First successful insulation measurement at ≤ 17.5 s
Undervoltage detection 0…500 V
(Bender configurable)

30 Hz ▸ Speed start measurement
Insulation measurement (only good/bad evaluation)
starts directly after power on ≤ 2 s;
PWM 5…10 % (good) and 90…95 % (bad)

40 Hz ▸ Device error
Device error detected; PWM 47.5…52.5 %

50 Hz ▸ Connection fault earth
Fault detected on the earth connection (Kl. 31)
PWM 47.5…52.5 %

Status output (OK_{HS})

OK_{HS} switches to U_S – 2 V
(external pull-down resistor to Kl. 31 required 2.2 kΩ)

High ▸ No fault; R_F > response value
Low ▸ Insulation resistance ≤ response value detected;
Device error; Fault in the earth connection
Undervoltage detected or device switched off

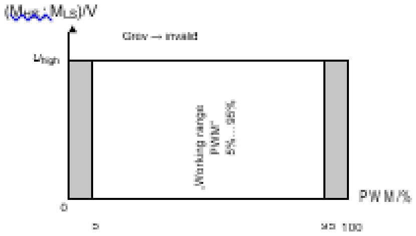
Operating principle PWM driver

- Condition "Normal" and "Undervoltage detected" (10 Hz; 20 Hz)

Duty cycle 5 % = > 50 MΩ (∞)
Duty cycle 50 % = 1200 kΩ
Duty cycle 95 % = 0 kΩ

$$R_F = \frac{90\,\% \times 1200\,k\Omega}{dc_{meas} - 5\,\%} - 1200\,k\Omega$$

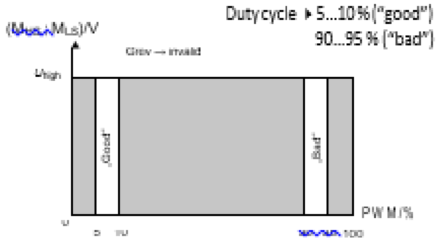
dc_{meas} = measured duty cycle (5 %…95 %)



Operating principle PWM driver

- Condition "SST" (30 Hz)

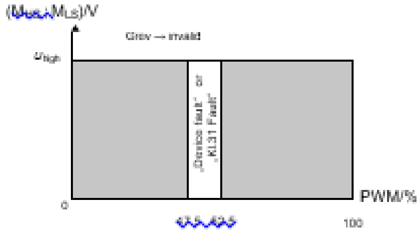
Duty cycle ▸ 5…10 % ("good")
90…95 % ("bad")



Operating principle PWM driver

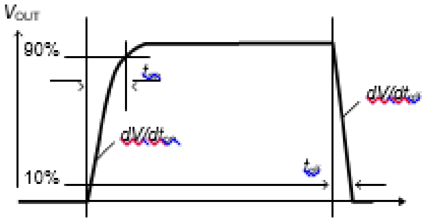
- Condition "Device error" and "Kl.31 fault" (40 Hz; 50 Hz)

Duty cycle ▸ 47.5…52.5 %



Load current I_L	80 mA
Turn-on time ▸ to 90 % V_{out}	max. 125 µs
Turn-off time ▸ to 10 % V_{out}	max. 175 µs
Slew rate on ▸ 10…30 % V_{out}	max. 6 V/µs
Slew rate off ▸ 70…40 % V_{out}	max. 8 V/µs

Timing 3204 (inverse to 3203)



EMC

Load dump protection	< 60 V
Measurement method	Bender-DCP technology
Factor	averaging
	F_{ave}
(output M)	1…10 (factory set: 10)

ESD protection

Contact discharge – directly to terminals	≤ 10 kV
Contact discharge – indirectly to environment	≤ 25 kV
Air discharge – handling of the PCB	≤ 6 kV

Connection

On-board connectors	TYCO-MICRO MATE-N-LOK 1 x 2-1445088-8 (Kl. 31, Kl.15, E, KE, M_{HS}, M_{LS}, OK_{HS} 2 x 2-1445088-2 (L+, L-); The connection between the respective connecting pins at L+ or L- may only be used as redundancy. Cannot be used for looping through!
Crimp contacts	TYCO-MICRO MATE-N-LOK Gold 14 x 1-794606-1 Conductor cross section: AWG 20…24
Enclosure for crimp contacts	TYCO-MICRO MATE-N-LOK receptor HSG single R -1445022-8 TYCO-MICRO MATE-N-LOK receptor HSG single R -1445022-2