Drive Train for an Electric Jet Ski Conversion.

THE UNIVERSITY OF WESTERN AUSTRALIA

Achieve International Excellence

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I would like to dedicate this thesis to my loving parents and my beautiful and amazing girlfriend.

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Abstract

The jet ski is a small water craft designed to carry one or two people for short distances on water, first commercially released in 1973, and commonly associated with water sports and family recreation. Although not as common as the motorcar or motor bike, Jet skis have never been considered an environmentally friendly vehicle due to their high level of noise and environmental pollution. Similar to small cars and motorbikes, they typically use 4 stroke petrol engines with capacity around 1500cc, and with petrol tanks up to 78 Litres.

The RevSki project is the first of its kind in Australia as it will test the performance characteristics of an entirely electric powered jet ski against a conventional petrol powered jet ski. The aim is to determine if an environmentally friendly, low emission electric jet ski can be competitive with petrol powered jet skis in the modern market. This thesis documents the design of the electric drive train including an in-depth analysis of all key design decisions as well as the selection key components, made throughout the design phase of the RevSki Project. The electric drive train includes the battery system, high and low voltage wiring, the motor, safety systems and control systems.

Contents

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Nomenclature

Greek Symbols

ρ_d Density

ρ_r Resistivity

Acronyms

AC Alternating Current

$BDCM$ Permanent Magnet Brushless DC Motor

BMS Battery Management System

CAN Controller Area Network

DC Direct Current

DIY Do It Yourself

ECU Engine Control Unit

HEV Hybrid Electric Vehicle

IM Induction Motor

KSI Key Switch Ignition

$LiFePO4$ Lithium Iron Phosphate

$LiCoO2$ Lithium Cobalt

kn Knots, $1kn = 1.852kmh^{-1}$

REV Renewable Energy Vehicle

rpm Revolutions per Minute

SRM Switched Reluctance Motor

W/kg Watts per kilogram

Wh/kg Watt hours per kilogram

Chapter 1

Project Introduction

As of 2013, there are no commercially available electric jet skis, hobbyist electric jet skis are rare, and those that do exist are underpowered [6], [7]. This will make the electric jet ski designed and tested by within this project, known as the *RevSki*, one of the world's first fully electric jet skis and potentially the world's first high performance electric jet-ski. Unsurprisingly this task doesn't come without its challenges. The concept is not new, as high performance electric cars have been on the market since 2008 [8] with electric outboard motors recently available [9] for commercial sale. The RevSki presents the interesting engineering challenge of applying existing technologies in a new application.

Engineering can broadly be understood as the task of applying scientific knowledge to solve technical problems. Phal et al describes the main tasks of engineers in 'Engineering Design: A Systematic Approach' as:

> *"To apply their scientific and engineering knowledge to the solution of technical problems, and then to optimise those solutions within the requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations."* [10]

The challengers associated with the RevSki project resonate with the main tasks of engineers as described by Phal et. al. The RevSki team applied their engineering skills to design and install a high powered electric drive system into the tight internal spaces of the donor jet ski whilst maintaining the highest level of safety in this challenging water prone environment.

It was the author's responsibility to oversee the design of the drive train for the RevSki. This included three main tasks as follows:

1. Researching and analysing each component of the drive train to facilitate the purchasing of the batteries, motor controller and auxiliary components.

2. Designing the wiring system for the main power components, ensuring that the required level of safety was maintained and all design requirements were met.

3. Ensuring the successful integration of individual parts of the RevSki project, this required liaising with other students on the team.

In addition to the three tasks outlined above, the author initiated the process of designing the required tests for determining the overall success of the RevSki project.

1.1 Project Overview

The term jet ski was introduced by Kawasaki motors in 1972 to refer to the first commercially successful personal water craft (PWC) [11]. A jet ski is a craft designed predominately for enjoyment over transportation but is also used for practical applications such as surf life saving [12]. All applications of jet skis require high performance, which has led to the development of jet skis with large petrol engines. This reliance on large petrol fuelled engines results in the release of significant volumes of pollutants in both the air and water as well has a high level of noise pollution [13]. A conversion to electric power would significantly reduce all sources of environmental pollution, however in order for an electric jet-ski to be commercially viable, it would need to compete with conventional systems in price, performance and safety.

The origins of the first electric car started with the demonstration of the principles of electromotive forces by Faraday in 1821 [14]. In 1881 Frenchman Gustave Trouvé demonstrated a functioning three wheeled electric tricycle at the International Exhibition of Electricity in Paris [15]. Moving forward to the modern day, electric cars are available for commercial purchase in the form of high performance cars such as the Tesla roadster [8] and commuter cars like the Nissan Leaf [16]. Books such as Brant's 'Build Your Own Electric Vehicle' [17] are aimed at non-engineers wishing to convert an existing petrol car to complete electric power. The success of these home conversions is available for the whole world to see on websites such as EV Album: http://www.evalbum.com/.

The UWA Renewable Energy Vehicle (REV) Project was started by Prof. Bräunl in 2008 and aims to 'revolutionise personal transport by building zero emission vehicles, powered by electricity from renewable sources'. [18] Since its formation, the UWA REV team have successfully built several fully electric vehicles including a high performance Lotus Elise, a competitive Formula SAE car, as well as a fleet of Electric Ford Focuses. This extensive experience is being applied to the challenge of building a high performance fully electric jet ski, the RevSki.

1.2 Project Goals

The primary goal of the RevSki project is to determine if electric jet skis are a viable alternative to petrol powered jet skis. This can be split into three key questions:

1. Can it be built?
2. Is it economically viable?
3. Will it perform competitively with the petrol powered jet ski.

The first question will be answered by the consturction phase of the project where the team will demonstrate that yes, it is practical to build an electric jet ski using available technology.

The second question will be answered in an additional study that will examine all the costs associated with the RevSki. The total of these costs will then be compared to new and second hand jet ski's of equivalent power to the RevSki. Included in this study will be a comparison of the cost per running hour of the RevSki against a conventional petrol powered jet ski.

The third question can be broken into three main categories; Raw Performance, User Experience and Reliability. For each category, tests have been devised to help compare the RevSki with a conventional jet ski, these tests are explored in more detail in Section 4. Raw performance is obtained by sizing a motor and battery system as large as possible. User experience, while closely linked to raw performance, also includes ease of use. The RevSki design must refer back to these aims at all points in the design process.

1.3 Project Stages

The RevSki is a multi year, multi discipline project. It has involved the contributions of many individuals and can be seen as a work in progress. For the putposes of this thesis, the RevSki project can be broken into 4 key stages; namely, Design, Construction, Testing and Evaluation.

1. Design Stage

The design stage involves research and analysis of existing electric vehicle designs and adapting them for the RevSki. This stage requires mechanical engineers to carry out the design of the battery box and the various mounting systems. The mechanical engineers are responsible for carrying out weight distribution analysis and stress calculations to ensure the final design will be safe. Electrical engineers are required to design the drive train, battery system and electronic safety systems. They are responsible for researching and choosing the correct components to ensure the success of the RevSki.

2. Construction Stage

This stage requires both mechanical and electrical engineers to oversee the installation components into the RevSki. However as construction progresses, engineers may be required to update or revise designs as problems arise. After the construction phase is complete testing will be carried out by the Rev Team.

3. Testing Stage

Stage Three involves performance testing the of RevSki. Tests should be carried out to determine the effectiveness of the RevSki under a variety of conditions. Research will be required to determine the main roles that jet ski's play, professionally and recreationally. Then tests must be designed to ascertain if these requirements are met.

4. Evaluation

The final Stage requires analysis of the results from the performance testing. Results must be compiled in order to answer the question 'Are electric jet ski's a viable alternative to petrol powered jet ski's?' This stage will involve mechanical and/or electrical engineers to evaluate the results of the testing stage.

The Context of this Thesis

At of the beginning of 2013 the team had taken possession of the donor jet ski and completed the preparation parts of Stage Two (construction), of removing the unneeded internal combustion engine including the fuel tank. Work had also begun on the mechanical designs for stage one. The author joined the project at this stage and started the design of the electric drive system. By the end of 2013 all the designs for the drive system and associated components were complete and purchased, thereby finishing Stage One.

The construction stage has already begun and is expected to be completed in the first half of 2014 with performance testing and analysis finished by the end of 2014.

1.4 Drive Train Concept

There are four main steps in the RevSki's drive train. First, energy is stored as chemical energy in the battery pack, the battery pack then converts the chemical energy to electrical energy in the form of DC power. Next, the Curtis Controller converts the DC power to 3 phase AC power as well as handling the challenging job of AC motor controller. The AC Induction motor then converts electric potential into rotational kinetic energy which is finally converted into liner motion by the impeller. Finally, the charger is responsible for getting energy back into the battery pack. Figure 1.4 shows the flow of power through the system. The drive train also includes several auxiliary systems, including safety system, cooling system and a 12V DC system.

The drive train design had to satisfy the following requirements:

- Safety
- Maximise Power
- Maintain the same weight distribution as the donor jet-ski
- Ease of operation

These requirements were met by utilising commercially available components and custom designed sections. Throughout the design process safety was always considered the number one priority.

The final design utilises a water cooled, AC induction motor and LifePO4 batteries. It is capable of a peak output of 60kW and a continuous output of 20kW. With a total battery pack size of 7.68 kWh, it is expected that the RevSki will be a high performance vehicle. Run time will be limited but should be sufficient for extensive on water testing. Section 2 covers each component of the drive train in detail and discusses the choices made throughout the design process.

Redesigning the water dynamics of the donor jet-ski was beyond the scope of the RevSki project, thus the decision was made to keep the weight distribution as close as

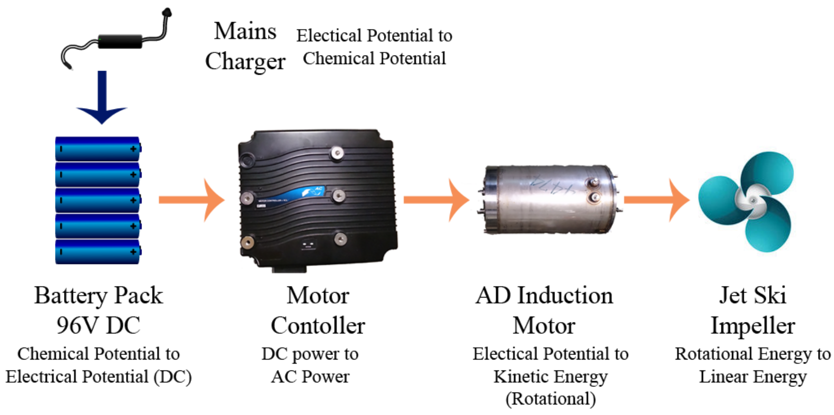


Figure 1.1: Main Drive Train Components

possible to the donor jet-ski, thereby limiting the size and location of components placed inside the jet ski. The original motor and fuel tanks were removed to make way for the new components with the existing impeller and drive shaft remaining. This left the major parts, such as the battery system, motor, motor controller, wiring system and cooling system, to be designed and installed.

1.5 Technology Selection Overview

All real world engineering projects like the RevSki must utilise existing technologies to best meet our design goals. This includes the research and the selection of many components with everything from a simple switch to the highly complex motor controller. Section 2 identifies the most important sections of the drive train as the batteries, motor controller and motor. For each of these components there is a large amount of available choice. In order for the RevSki to be successful each one of components can only be purchased after careful consideration. Section 3 covers in detail the authors process when selection the right components for the RevSki. When considering alternative technologies the following criteria was used:

1. It must be commercially available.
2. It must be safe.
3. It must be cost effective, ie looking at power to cost ratio.
4. It must be a performance device, ie looking at power to weight ratio.

Initially after researching different battery types used in similar electric vehicle conversions, these 3 battery types where selected for further consideration; Lead Acid, LiFePO4 and LiCoO2. After comparing power and energy to weight and cost ratios along with life cycle and safety considerations the LiFePO4 battery was chosen as the most appropriate for the RevSki. LiFePO4 batteries have high energy and power density and are significantly safer than the LiCoO2 batteries for only slightly higher cost.

Secondly, motor types were considered. Starting with a broad comparison of AC and DC motors. The choice was narrowed down to comparing series wound DC motors and Induction AC motors. It was found that Induction AC motors are far more efficient. They are also easier to water cool and water proof both of which are a significant advantage for the RevSki. In the end a custom build AC induction motor by Submersible Motor Engineering was selected for the RevSki.

For the AC motor a specialised controller was required. The controller is responsible for converting the DC power to three phase AC and controlling the motor thus it must be matched specifically to the motor. The controller selected is a Curtis 1238-76XX Controller.

1.6 Performance Test Design Overview

As part of the author's work throughout 2013, the initial work on designing performance tests for the RevSki was carried out. In order to determine the success of the RevSki it will be tested against a comparable petrol jet ski in a variety of scenarios. These include raw performance tests such as acceleration and top speed as well as situational tests such as water skiing, racing and surf lifesaving. The author recommends that members of the various communities involved with jet skis, such as surf lifesaving clubs, should be interviewed to help design appropriate tests for the RevSki.

Chapter 2

Drive Train Design

2.1 Drive Train Design: Introduction

The Drive train represents the main component of RevSki conversion. The Drive train includes the batteries, wiring, controller and motor. It was the author's responsibility on the RevSki Project to handle the overview the drive train, ensuring that all components would meet the design requirements of the RevSki and would work efficiently together. The RevSki is a team project requiring the multidisciplinary skills of several engineering students. With respect to the RevSki's drive train, the battery system is discussed in detail by Madappuli [19] and Jayamanna [20], the safety sub systems by White [21] and the cooling system by Clark [22].

This section will focus on electrical design of the battery system, motor, motor controller and the wiring, concentrating on how all these components will work together. The main design requirements for all components of the RevSki are:

- Guarantee the highest level of safety.
- Maximising performance and output power.
- Maintaining the same weight distribution as the donor jet-ski.
- Ensuring that all systems must be easy to operator.

The RevSki presents some unique design challenges above a standard electric vehicle conversion. Most important, is the safety concern of mixing water and high power electrics. In each stage of the design process the ingress of water into the system must be considered. Two main methods are utilised for mitigating the dangers presented by water, prevention and detection. The interior of the jet-ski has been completely sealed as a first stage prevention method. Secondly where possible, delicate components are placed inside sealed containers and water proof connectors are used in all cable joins to prevent contact with water. Finally water sensors are utilised to detect any water inside the jet ski and will halt the operation of the jet ski, as a breech of the water proofing could damage the delicate electrical components and pose a safety risk to the rider.

2.2 Drive Train Design: Literature Review

Electric vehicle conversions are nothing new, Brant published the first edition 'Build your own electric vehicle' in 1994 [17]. Since then websites such as EV album `http://www.evalbum.com/` have grown in popularity with over 700 unique visitors a month according to Alexa page rank [23]. Additional websites provide design blogs of individual conversions like MetricMind CEO Victor Tikhonov's Audi conversion. [24]. Several forums exist for communication between like minded individuals such as `http://www.diyelectriccar.com/forums/` which gets over 30,000 unique visitors every month [23]. This is just the tip of the iceberg, researching online will provide countless accounts from a large variety of sources on tips and ideas for electric car conversions, demonstrating the global interest in electric vehicles.

More recently (2013) Brant has released a third edition to his book that serves almost as "gospel" within the electric vehicle community. The book provides an up to date overview on the conversion process, from selecting a donor vehicle and parts, to wiring up the braking system and installing a new heater.

The academic world is also full of papers, covering the technical details of electric vehicle design and conversion. Whilst many of these papers focus on very specific areas such as new battery or motor technologies, the Rev Team as been able to gain significant benefit from several sources. Fenton, provides an overview of various electric drive train designs [25] as does Ehsani [26] and Chan [27], these papers were used as starting point for the design of the RevSki drive train. Toliyat and Kliman's 'Handbook of electric motors' [28] is an invaluable resource into electric motors and control systems, describing in detail every aspect of motor control for a variety of motors including the AC induction motor used by the RevSki.

Hazuku et. al. from the Tokyo University of Marine Science and Technology have successfully built a fully electric powered boat, capable of carrying up to 11 crew [29]. The boat, called "RAICHO-S", consists of a 50kw (Peak) Interior permanent magnet motor driving an internal jet system, similar to the impeller used by the RevSki. The motor is powered by 22.5kWh of batteries this gives the "RAICHO-S" a run time of 45 minutes at its top speed of 10kn. At this speed the motor is only providing 25kW. The difference between this continuous maximum power and the peak power allows the "RAICHO-S" to accelerate faster in short bursts. The "RAICHO-S" is designed as a short range transport vessel for diving operations. Compared to the RevSki, the "RAICHO-S" is both a heavier and slower water craft, however, they have similar motor power, thus backing up the expectation that the RevSki should have a high level of performance. However, the greater size of the battery pack on the "RAICHO-S" vessel, means that it has a much longer run time than the RevSki.

In view of the wealth of material available from both enthusiasts and scholarly sources, it is surprising that electric jet skis have been given so little attention. This thesis document and the other documents produced by the RevSki team, will represent some of the earliest literature available on electric jet ski conversion. While many of the design principles are similar to that of an electric car conversion, a significant portion of the work is completely unique to this project, owing to the focus on small personal water craft.

2.3 Drive Train Design: Overview

The existing drive from the donor jet ski is a direct drive system, where the motor is connected directly to the drive shaft with no clutch or gear box. [30] A clutch is not required in the drive train because the impeller can continue to spin at idle speeds without generating any significant thrust. Reverse is then provided using a mechanical plate that redirects the flow of water from the impeller back underneath the jet ski, additionally an electric motor was selected with a rpm matched to the impeller this means that there is no requirement for a complex gearbox.

The design brief for the RevSki conversion is to re-use as much of the existing system as possible. To that end, the electric motor will take the place of the petrol motor as an almost drop in replacement. The same drive shaft will be used, again there is no requirement for a gear box or clutch as the RevSki will utilise the existing reversing system. The control system of the AC motor allows for reverse operation with no extra complexity. This will be investigated during the testing stage of the RevSki project to determine if the reversing and braking capabilities of the RevSki can be improved with the new drive system.

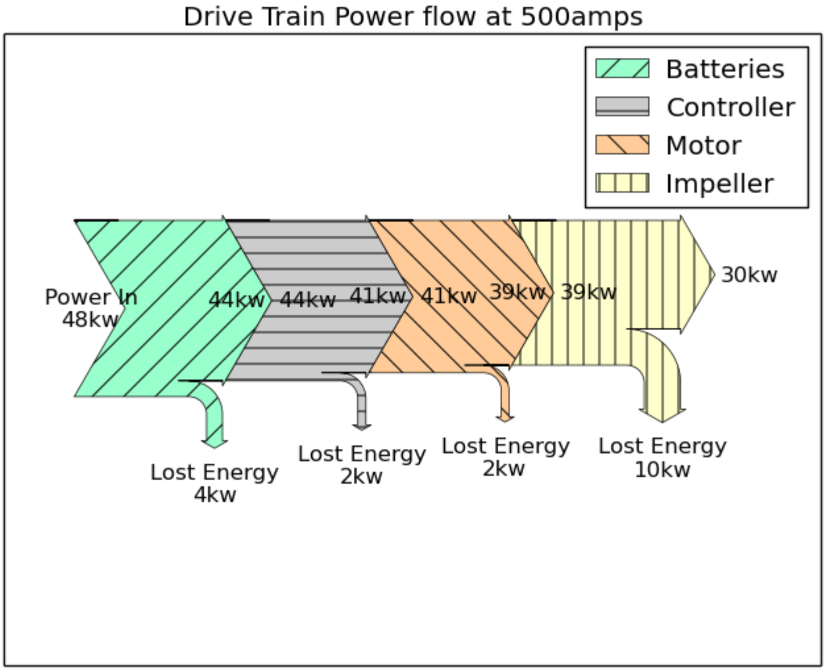


Figure 2.1: Power Flow

The drive train of the RevSki is conventional to standard electric vehicles. Batteries store energy as chemical potential energy and have the ability to convert this stored chemical potential into electric potential energy as DC voltage. A wiring system then connects the batteries to a controller, which converts the DC voltage into AC. A second wiring system connects the controller to the motor. The motor is responsible for converting the electric potential energy into rotational kinetic energy. The motor is connected via a drive shaft to the impeller which finally converts the rotational kinetic energy into linear energy and drives the jet ski forward. Figure 2.3 shows the flow of power through the system with estimated losses at appropriately 50 kW.

Figure 2.3 shows the location of the main components in the RevSki. The batteries will be placed in a box mounted towards the front of the jet ski, located near the old fuel tank. The electric motor is placed low down in the hull and is directly connected with the drive shaft. A bridge has been designed, by Clark [22], that will go over the motor, providing a mounting place for the controller and auxiliary components.

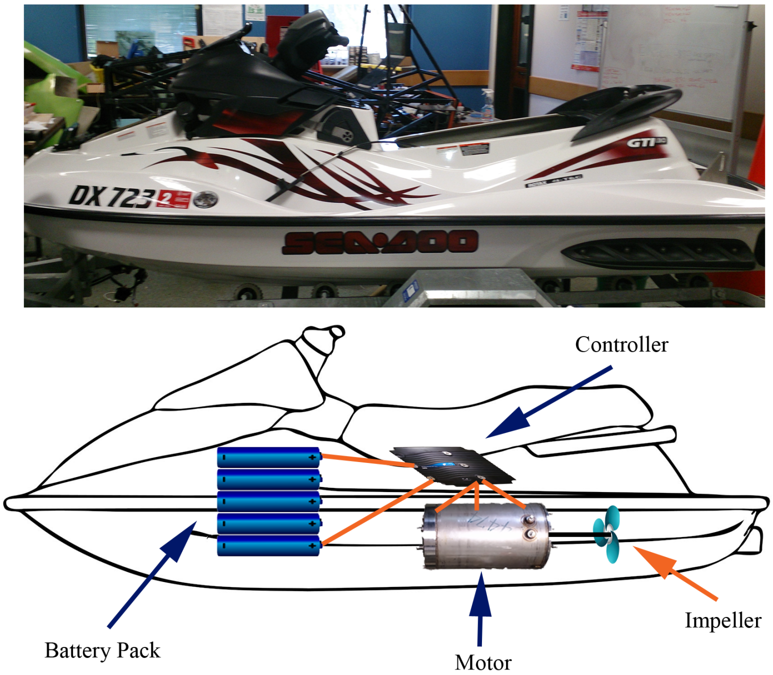


Figure 2.2: Layout of Main Components in the RevSki

2.4 Safety Design Considerations

Safety during the design phase of the project was a major priority. Before and during the design process, a risk assessment was completed for each major point of failure. A record of these can be viewed in Appendix A. After each risk was identified it was categorised using a risk matrix also available in Appendix A. Each risk was given a likelihood score between ‘rare’ and ‘certain’; indicating that the event will occur. Next they were given a severity score between ’Negligible’ and ’Catastrophic’, an example of each severity category is given in table 2.1. These scores are then multiplied to give a total risk score and labelled as:

- Extreme, 101+.
- High, 21 to 100.
- Medium, 6 to 20.
- Low, 0 to 5.

Table 2.1: Description of risk severities

Severity	Examples
Negligible	Jet ski stops operation or a fuse has to be replaced.
Marginal	Damage to minor components eg sensors and relays.
Serious	Minor injury to rider or damage to major components eg motor or batteries.
Critical	Major injury to rider or damage to multiple major components.
Catastrophic	Danger to others, complete destruction of the RevSki, death of rider.

For any risk about than low, controls must be put into place. Preventative measures such as water proofing have been used to lower the likelihood of a failure occurring. Reactive measures such as temperature cut-off's are used to reduce the severity of risk. See Section 2.8 for more details on the safety subsystem. The engineering controls are discussed in the relevant sections of this document. Some of the controls used are not engineering controls but rather, operator training based, and will be further discussed:

Continuous water testing

The presence of water inside the battery box could have critical consequences. As it is not possible to satisfactorily mitigate this risk entirely with the engineering controls, water proofing and fuses must be put into place before the RevSki can be operational. All the waterproofed sections must be regularly inspected, including between every operation of the RevSki. Any wear or faults in the waterproofing must be repaired prior to on water operation of the RevSki. Even with all the controls in place, this remains an ongoing medium risk of which all operators must aware of before commencing any work on the RevSki.

Training for working on the RevSki

The internals of the RevSki contain several High Voltage cables (<100 V) capable of carrying very high current (approx. 1000 amps) which poses a significant risk to personnel. All wires coming in and out of the battery box are fused to limit the chance of a short circuit. All high voltage wires are coloured orange as per the National Guidelines for electric vehicles [31]. Additionally, a manual cut off is installed (see Section 2.6) that includes a large Red-button that must be depressed before conducting any works on the RevSki. Finally training must be conducted for everyone who will be working on the RevSki so that they understand these risks and controls.

Rider Training

Even with all the safety systems in place, the RevSki is still a high performance water craft and inherits all the dangers associated with conventional jet skis. In order to mitigate these risks, anyone who rides the RevSki must hold a valid license (Restricted Skippers Ticket) and be wearing appropriate PPE. Given the prototype nature of the RevSki, another vessel must be present whilst testing the RevSki to be able to render assistance if and when necessary.

2.5 Batteries Design

The batteries form the power house of the electric vehicle and can be the limiting factor of not only run time but also peak performance. After considering several options the 38120 LifePO4 batteries manufactured by Headway-Headquarters, LLC [1] and sold by EV Works, Australia, were selected for the RevSki (see Section 3.3 for more detail). This section will focus on the electrical design of the batteries including logical layout, safety systems and wiring.

2.5.1 Battery Mounting and Cell Layout

The batteries were placed in a custom designed battery enclosure [20]. The enclosure is then mounted in place of the existing fuel tank. In order to comply that the main design parameter of maintaining weight distribution is followed, the total weight of the batteries was limited to approximately 80kg. The Headway batteries are 330g each [1] allowing us to include 240 batteries in the RevSki. The next limiting factor is maximum voltage. The RevTeam has imposed a 100VDC limit for student projects that the RevSki must comply with. Each of the headway batteries has a nominal cell voltage of 3.2V, wiring 30 batteries in series gives a combined voltage of 96V, which is within the 100V max. At each voltage level 8 batteries were placed in parallel. This battery configuration is known as 30s8p.

This gives the total pack the follow parameters based of manufacturer's specifications:

- 8 batteries in parallel per cell.
- 30 cells to make the total pack.
- Nominal voltage of 96V.

- Nominal capacity of 80Ah, 7.7kWh.
- Peak discharge current 10C, 800A.

2.5.2 Connecting the Batteries: Bus Bars

The batteries are provided with bus bars by the manufacture for connecting the batteries into packs. Figures 2.5.2 and 2.5.2 give the dimensions of the bus bars. Equations 2.1 to 2.6 describe how to model the temperature in a conductor eg wire or bus plate. The following physical constants are used:

- ρ_r electrical resistivity, of copper $1.59 \times 10^{-8}\Omega.m$
- ρ_d density, of copper $8,940kg.m^{-3}$
- c specific heat, of copper $385J.kg^{-1}.K^{-1}$

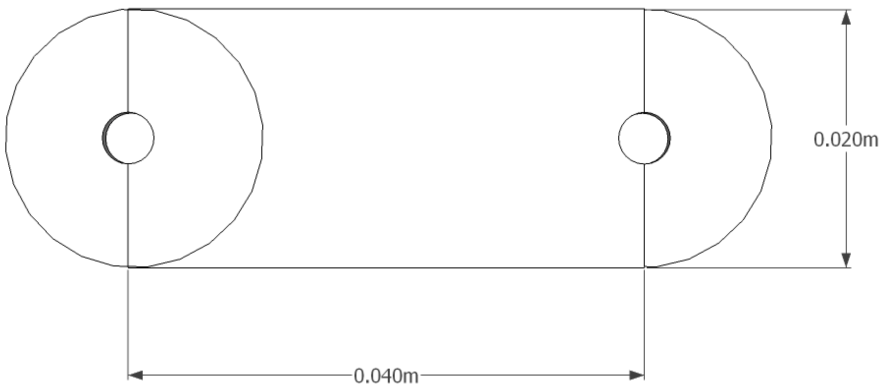


Figure 2.3: Bus Bars Used: Top view

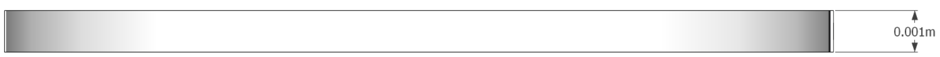


Figure 2.4: Bus Bars Used: End view

Eq 2.1 gives the resistance of the bus plate in Ω. Eq 2.2 gives the heat power generated in the bus plate in W. Eq 2.3 gives the mass of bus plate in kg. Eq 2.4 gives the heat lost to the air around the bus plate. Letting $T[t]$ be the temperature of the bus plate above air temperature with respect to time (t). Solving Eq 2.5 gives Eq 2.6 which shows the temperature of the bus plate with respect to current, cross sectional area A_1, surface area per metre A_2, starting temperature, the physical constants and time.

By graphing the change in temperature of the bus plates over time at the maximum operating current of 650 amps, (see Figure 2.5.2) it is clear that a single plate would not be sufficient. In areas where maximum current would be present 3 bus plates are used, limiting the maximum increase in temperate to less than 50 degrees above ambient. This increase in heat may still cause problems for the RevSki. For the first stage of the RevSki project this risk will be controlled by monitoring the temperature of the batteries and ceasing operation in case of extreme heat. Future works for the battery system may include forced air and liquid cooling.

$$R = \rho_r \frac{l}{A_1} \tag{2.1}$$

$$P = R \times I^2 \tag{2.2}$$

$$m = l \times A_1 \times \rho_d \tag{2.3}$$

$$Q = k \times A_2 \times T[t] \tag{2.4}$$

$$T'[t] = \frac{P - Q}{c \times m} \tag{2.5}$$

$$T[t] = \frac{I^2 \rho_r + e^{-\frac{A_2 k t}{A_1 c \rho_d}} \left(-I^2 \rho_r + A_1 A_2 k T_0\right)}{A_1 A_2 k} \tag{2.6}$$

Where :

R : Resistance

ρ_r : Resistivity

l : Length of the conductor

A_1 : Cross sectional area of conductor

P : Power generated as heat

m : Mass of the conductor

ρ_d : Density of the conductor

Q : Heat lost to enviroment from the conductor

k : Heat transfer coefficient for the conductor

A_2 : Surface area of the conductor per unit length

T : Difference in heat between the conductor and the enviroment

t : Time

T_0 : Difference in heat between the conductor and the enviroment at time 0

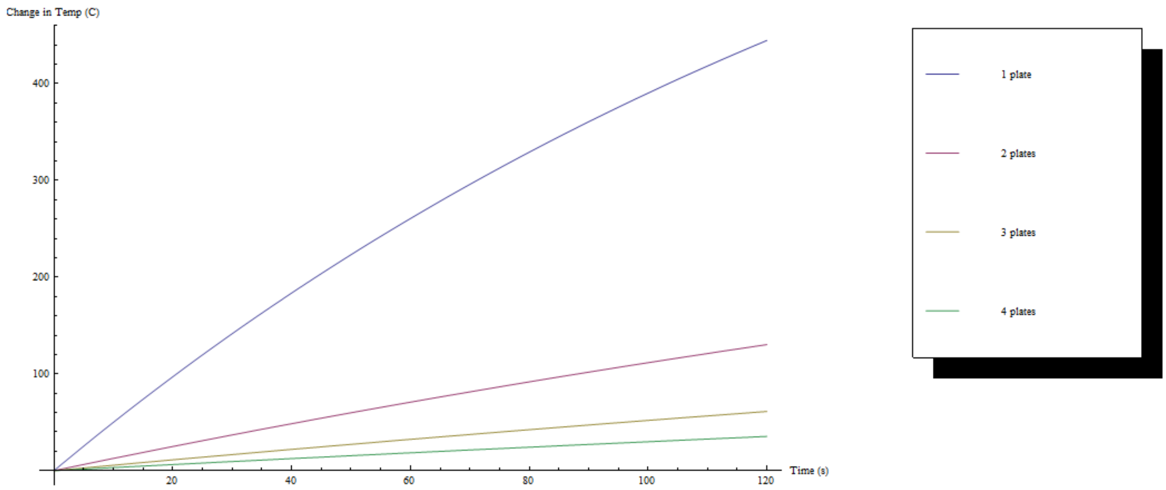


Figure 2.5: Bus Plate temperature at 650 Amps using eq 2.6

2.5.3 Battery Management Systems

The LiFePO4 battery cells are very sensitive to voltage change and may become unstable at high ($> 3.6V$) or low ($< 2.0V$) voltages [1]. To prevent this situation, a battery management system (BMS) is to used monitor the battery voltage. If the battery voltage is close to unstable, the BMS will notify the safety subsystem, which will then shut down the operation of the RevSki motor. More sophisticated BMS's can also balance voltages across cells by allowing small currents ($< 1amp$) to flow between the cells. This adds more complexity to the overall system and was determined to be unnecessary for the RevSki. For more details on the BMS see [19]

2.5.4 Battery Efficiency

The battery efficiency can estimated by analysing each cell's internal resistance and maximum current. The cells internal resistance is $< 6m\Omega$ [1] so with an operating current of 500 amps (62.5 amps per cell) the efficacy is 88% using Eq 2.7. Figure 2.5.4 shows the discharge curves of the battery cell at various currents, this graph shows how the battery efficiency decreases as load increases.

$$\begin{aligned} eff &= \tfrac{V_n-(IR_I)}{V_n} \times 100\% \\ Where &: \\ I &: \text{ Current} \\ R_I &: \text{ Internal Resistance} \\ V_n &: \text{ Nominal Voltage} \end{aligned} \tag{2.7}$$

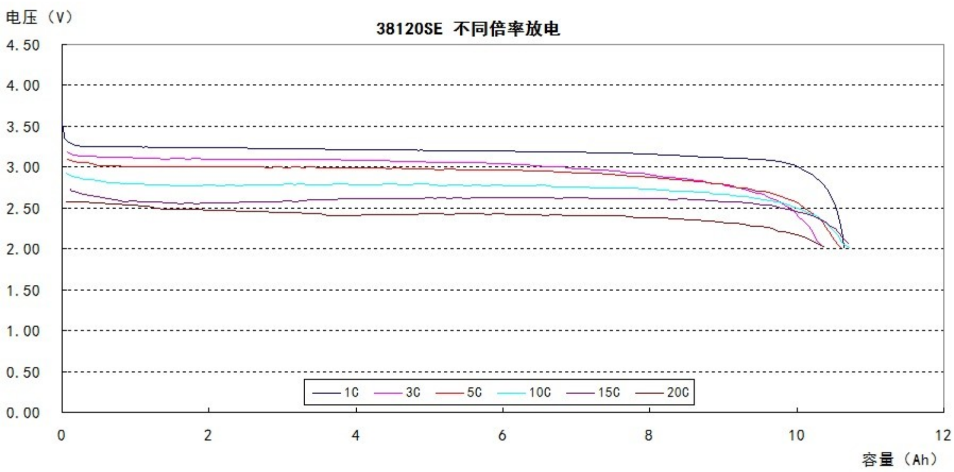


Figure 2.6: Discharge Curves for the Headway 38120S battery [1]

2.6 Wiring Design

A well designed wiring system is critical for the success of the RevSki conversion. The wiring system of the RevSki is responsible for transferring power from the batteries to the controller and motor within safe limits. The design requirements for the wiring system are:

- Safety
- High current 96V to the controller
- Low current 96V to the controller with integrated safety cut off
- 12V DC for auxiliary system
- Charging connections
- Monitoring system

The wiring diagrams used for the RevSki were created by the author and are included as Appendix B. Figure 1 shows the complete wiring diagram. Figure 2 shows in detail, the various connections to be made to the Curtis controller. Figure 3 shows the circuit required to connect the Curtis controller to a Windows XP computer.

2.6.1 Wiring Design: Physical Disconnects

There are two main concerns for safety within the wiring system. The first is the requirement to disconnect the high power motor and controller from the batteries in the event of a system failure, the second is overheating or damage to components due to high current.

There are two different mechanisms for disconnecting the batteries from the controller, both systems use mechanical disconnects so there is no chance of solid state relay failure. [32] First, an emergency stop button is installed as the closest component to the batteries (es_1) . The RevSki is using the 'Nanfeng 250A Emergency Disconnect Switch' available from EV Works [4] As the Nenfeng is only rated to 250A continuous current two switches are used in parallel for a combined continues current of 500A. The Nanfeng is operated manually by pulling out the switch to make a connection or pushing the switch in to break the connection. The switch is designed so that minimal force is required to push it back into the off position. In the event of any dangerous situation the operator can hit this 'emergency stop button' cutting all power to the RevSki's systems.

Second high power relays known as 'Contactors' are used. The RevSki has two high current contactors (cn_a, cn_b), 'Tyco Kilovac 500A 320VDC LEV200 Contactor' purchased from EV Source [33]. The contactors operate with a magnetic coil that includes magnetic blow-outs to allow safe disconnecting on high currents up to 2000 amps. The contactors on the negative line (cn_b) is connected directly to the 12V auxiliary power line that completely disconnects the controller from the batteries when the safety system is disabled. Contactor A (cn_a) is located in the positive line and is controlled by the Curtis controller. Contactor A will only close when the controller is powered and healthy.

The third contactor (cn_ks) is a smaller contactor, 'Nanfeng ZJW50A Contactor', that is placed in the 'key switch line' of the Controller. This line provides power to the logic side of the controller without which it would not be possible for the controller to power Contactor A, thus cn_ks can be used to isolate the controller from the battery system. This design is in accordance with the safety guidelines for the controller system [34].

A simple mechanical switch (part: S1042 from Altronics [35]) is used to control power to the DC-DC converter.

Every component connected to the battery or the 12V output of the DC-DC converter is fused. This greatly reduces the chance of a downstream fault causing a short circuit of the battery pack. In order to keep the risk as low as possible each fuse is sized to match the maximum expected current. Table 2.2 lists the fuse sizes purchased for the RevSki.

Table 2.2: Fuse Sizing for the RevSki

Drawing ref	Position	Size
fu_ch	charging	30A
fu_ep	TBS Expert Pro	Built in
fu_dc	DC DC converter	Built in
fu_ma	Main	1000A
fu_ks	Key Switch	20A
fu_12	12V power	20A
fu_bms	BMS system	1A

2.6.2 Wiring Design: Monitoring

A 'TBS E-Xpert Pro' [36] is used to monitor the battery system and power usage. The TBS is a combination micro processor, current meter and voltage meter. Voltage is measured directly from the main battery pack. Current is measured by measuring the voltage drop across a shunt resistor placed on the negative terminal of the battery system. The micro processor then reads and records these two measurements periodically and allows for statistics such as State of Charge and Time remaining at current power. This information is then made available to the rider through an LCD display.

2.6.3 Wiring Design: Safety Standards

Wiring was carried out following the guidelines of the Australian Standards Wiring Rules [37] and 'Electrical installations: Marinas and recreational boats' [38]. Section 4.9 and 4.10 in [38] cover the requirements for mounting batteries in boats. Section 6 in [38] covers shock prevention in AC systems over 50V, this protection is provided by the Curtis controller. Fuses were installed as per section 7.3 [38]. Table 6 from [38] gives recommendations for cable size for continuous current. Our continuous current rating is 80amps for 1 hour, 240A for 20 minutes or 650 amps for 2 minutes. The final cable size used was $70mm^2$. As the RevSki differs from a standard marine power design, we performed analyses of the cables using equation 2.6 to determine that $70mm^2$ would be sufficient. For terminating the cables 'captive spade 'style terminations are used as per section 10.2 from [38].

In addition, safety standards from the 'National Guidelines for the Installation of Electric Drives in Motor Vehicles' [31] where used where appropriate. For example the use of orange coloured cabling for high voltage wires.

2.7 12V Auxiliary system

The RevSki requires a 12V DC power system for powering auxiliary components including the safety subsystems, water pump and contactors. The power requirements for each component is shown in Table 2.3. Four possible methods for providing the 12V supply where considered and are shown in Figure 2.7.The advantages and disadvantage of each method are outlined below.

In Option A, power is provided from four of the 3.2V battery cells. Whilst this presents the simplest solution this will lead to unbalanced discharging of the main battery pack, which is extremely undesirable as it could lead to permanent damage of the battery pack.

Options B and D require an additional 12V battery such as a car battery. In both cases this auxiliary battery will require charging. In Option B this is provided from the main battery pack through a DC-DC converter. For the separated case of Option D, an

Table 2.3: 12V Auxiliary system Power Requirements

Component	Max current (Amps)
Water Pump	2
BMS	0.01
Safety subsystem	2
Contactor B	1
KSI relay	1
Total	6.01

alternative charging solution would be needed, for example removing the auxiliary battery and charging from mains power. Both Options B and D allow the auxiliary systems to remain powered even when the main battery pack is disconnected.

Option C shows the DC-DC converter providing all the power required for the 12V auxiliary systems with no auxiliary battery. This system is not capable of providing power to the auxiliary systems when the main battery pack is disconnected.

Because the RevSki has low auxiliary power requirements and no requirement to run the auxiliary system without powering the main system the extra complexity of Options B and D provide no benefit. Thus the RevSki team choose to adopt Option C.

Option C requires the use of a DC-DC converter. A DC-DC converter is a device the is capable of transforming one DC voltage to another. Schupbach [39] describes in detail the operating principle of various DC-DC converter designs with a specific attention to electric energy vehicle applications. For the RevSki a commercial available converter is sufficient for our needs. The RevSki requires a 96V to 12V converter with a minimum output current of 10A (the total value from Table 2.3 plus an margin to allow for future expansion).

Commercial converters come in two main types, isolating and non-isolating. An isolating converter does not share a common ground between the high and low voltage sides. While an isolating converter does share a common ground between the inputs and the outputs. An isolating converter is more flexible as it can easily be converted to a non isolating converter by connecting the negative terminal of the input with the negative terminal on the output. Appendix C gives a summary of the DC DC converters considered for the RevSki.

The DC-DC converter used in the RevSki is a 'HWZ Series DC-DC Converter 96V to 12V 300W' purchased from Kelly Controlls LLC [40]. This converter will convert the 96V main battery pack voltage to the 12V required for the auxiliary systems and has a

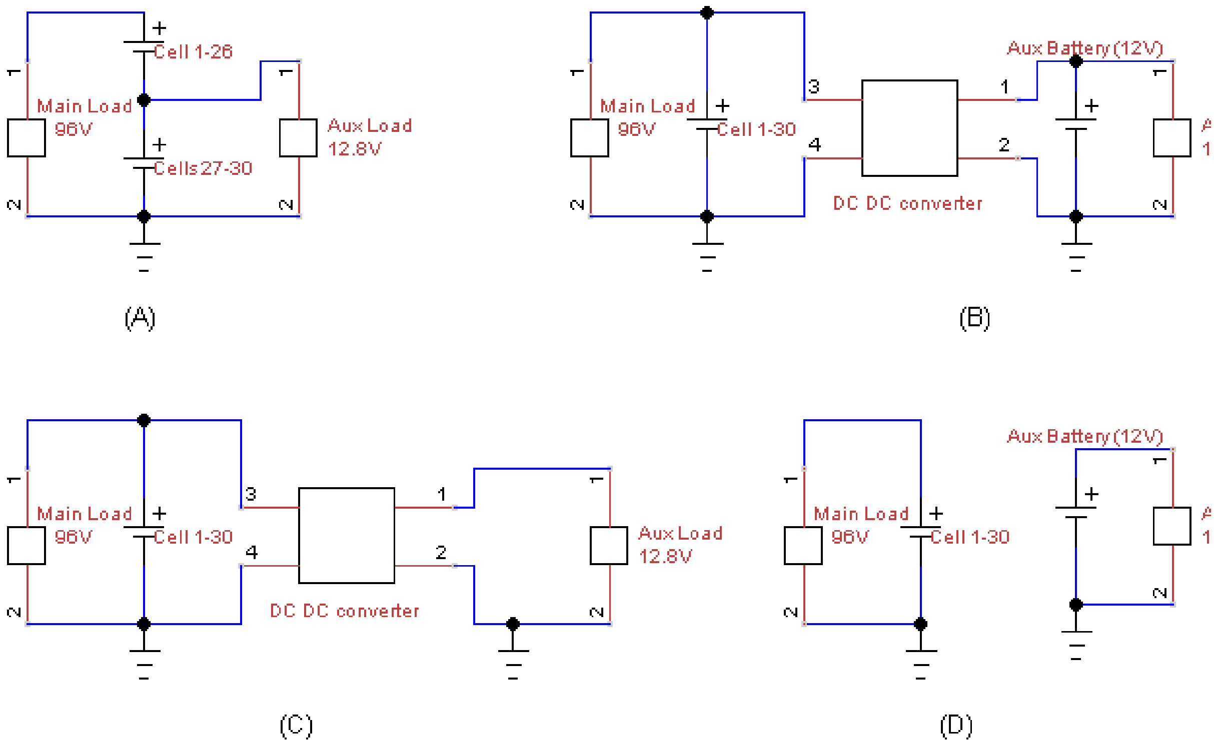


Figure 2.7: 12V power supply wiring options

maximum output current of 25 amps which is well above our requirement of 10 amps. The converter is an isolated type which gives the Rev Team the flexibility of either operating configuration and has all the standard safety features required for automotive electronics.

2.8 Safety Subsystem

The safety subsystem is a custom engineered solution, designed by White [21]. The system is split into 2 sections; a hard-wired emergency cut-off and software controlled warnings.

The hard-wired section is a modular series of sensors including water sensors, temperature sensors, charging sensors and rider sensor. Each sensor controls a relay that is designed as fail safe, so that current will only flow through the relay if the sensor is active and healthy. Fail off means that in the event of a system failure, such as a break in a sensor wire, the system will shut down. Each sensor module is then chained together to provided a final healthy output of 12V. The safety system integrates with the main drive system through the kill switch relay (cn_ks, thus it is capable of fully disabling the motor controller and preventing any power flowing to the motor. The hard wired system also integrates with the charger to prevent charging in the case of an unsafe situation.

Complementary to the hard-wired system is an Arduino controlled system. The Arduino is an off the shelf microprocessor the possesses a number of inputs and outputs. The Arduino will be wired to variable temperate and water sensors. This allows for soft limits to be programmed into the RevSki. When a limit is reached, an alarm will sound alerting the driver to the unsafe condition, before power is cut by the hard-wired system.

2.9 Motor Design

The motor forms the power house of the RevSki. The selection of the motor is an important part of the project and is discussed in detail in section 3.4. The motor selected is a 3-phase induction motor [28] rated at 96V shown in Figure 2.9. The motor was developed by Submersible Motor Engineering Pty Ltd (SME) and ifs fully waterproof. The full specification sheet for the motor is attached as Appendix D. Important values to note from this specification sheet is the rated efficiency at 50kW of 95.00% and the rated shaft speed of 7940 rpm. This is matched to the maximum rpm of the existing petrol motor [30]. .

Figure 2.8: SME Motor

Part of the aim of the RevSki project was to re-use as much of the original systems from the existing Jet Ski as possible. The original motor was connected directly to the drive shaft for the impeller. Jayamanna [20] discusses the challenges and solutions to mounting the new electric motor in place of the existing petrol motor. The electric motor is significantly smaller and denser then the existing petrol motor however the design still allows the re-use of the existing mounting points and the existing drive shaft.

The 5% power loss summarised in Table 2.4 amounts to 2.6kW when operating at 50kW output power. This 2.6kW is lost as heat that must be removed from the motor to sustain continuous operation. This will be achieved using a closed loop cooling system that utilises the existing heat exchange mounted in the base of the jet ski. The cooling system will be capable of completely dissipating this excess heat as shown by Clark [22].

Table 2.4: Power loss in motor at 50kW and 96V

Losses	Power (W)	%
Copper Loss of Stator Winding	647.7	1.23
Copper Loss of Rotor Winding	1013	1.92
Iron-Core Loss	421.2	0.800
Frictional and Windage Loss	295.52	0.561
Stray Loss	250	0.475
Total Loss	2,628	4.99
Input Power	52,630	100
Output Power	50,000	95.0

2.10 Controller Design

The AC induction motor requires a complex control system that also servers as an inverter to convert the DC power to the AC power as needed by the motor. As discussed in section 3.5 the Curtis 1238 is the most suitable controller for the RevSki project, pictured in Figure 2.10. The Curtis 1238 is rated for 96V and 650 amps over a 2-min period [34] and includes a variety of safety and user features, the most important of which will be discussed here. Figure 2 from Appendix B shows all the connections that need to be made to the Curtis controller for the RevSki.

2.10.1 Controller wiring

Pins B+ , B-, U, V and W are all heavy duty connections that are made with 8mm lugs. These are the connections for carrying the full power of the system through the controller to the motor. B+ and B- connect directly to the main battery pack through the two main safety contactors.

The remaining pins are considered low current and are made using a single water proof connector (AMP - 776164-1 Figure 2.10.1). Available from `http://uk.farnell.com/`

Figure 2.9: Curtis 1238 Controller

te-connectivity-amp/776164-1/connector-recept/dp/1654497. This is then broken out to a single waterproof connector for each component as shown.

Figure 2.10: AMP - 776164-1 for Curtis Controller

Pin 1 is known as the 'Key Switch Ignition line' this pin serves multiple purposes. It is connected to the positive (96V) terminal of the main battery pack through the KSI relay. This pin provides all the power for the auxiliary systems of the controller including safety systems, 12V & 5V logic systems (through an internal voltage converter), capacitor pre-charge and output drivers. As well as providing power to the controller, this line serves as a safety line, cutting power to this line will cut power to pin 6, resulting in contactor A opening and completely disconnecting the controller from the main battery pack. The KSI relay is controlled from the safety system thus allowing the safety system to completely isolate the controller and motor in the case of an unsafe situation.

The KSI line also provides power for capacitor pre-charge. The controller contains several large capacitors that must be charged prior to operation. If the controller was to be connected to the battery pack via the Main line (B+) before pre-charge, the capacitors would draw extreme current (>1000 amps) that would damage the system and could cause sparking. Instead the capacitors are trickle charged with power provided by the KSI line. Pin 6 will not be powered until the capacitors are fully charged.

Contactor A is connected between pins 13 and 6. Contactor A is one of the two main contactors that is placed in the main power supply line to the controller. Thus allowing the controller's safety features to control the power supply. If the controller detects an unsafe condition, such as over heating, it will remove power to pin 6, thus disconnecting itself from the main battery pack.

Pins 8-14 and 24 are inputs to the controller consisting of both analog and digital inputs. These switches can be used for a variety of programmable situations. For the RevSki we are only using switch 7 (pin 13) and switch 2 (pin 8). Switch 2 is run through a variable thermoresistor built into the motor to monitor the motor temperature. Switch 7 is the forward switch to indicate that forward motion is required, as the RevSki is not set-up for reverse this switch is wired directly to the +5V line (pin 26). The controller has built in support for this type of wiring, so pull up or down resistors are not required. Pages 8-22 of the Curtis manual provides greater detail into the wiring for the controller. [34]

2.10.2 Rotational Encoder

An encoder is required by the controller to provided direct feedback on the motors shaft's position and speed. The encoder user in the RevSki is a LARM magnetic incremental encoder (MIRC 325/64 PB) pictured in Figure 2.10.2. The encoder is wired into pin 26 and 7 for power and pins 31 and 32 for communication. The controller is limited to a maximum encoder frequency of 10 kHz. This crates a limits on the maximum rpm of 9375rpm due to the accuracy of the encoder, as shown in Eg. 2.8. As the motor is only rated to 8000rpm (Appendix D) this will not limit the maximum rpm of the motor. The specifications sheet for the encoder is attached as Appendix E.

$$EncoderMaxRPM = \frac{10000(Hz) \times 60(s.min^{-1})}{64(pulses.r^{-1})} = 9375rpm \tag{2.8}$$

The controller has a maximum electrical frequency of 300 Hz, as the motor is a two-pole motor this places a limit of 18000rpm on the motor due to electrical frequency, see Eq 2.9. As this is well above the motor's maximum rpm, the controllers maximum electrical

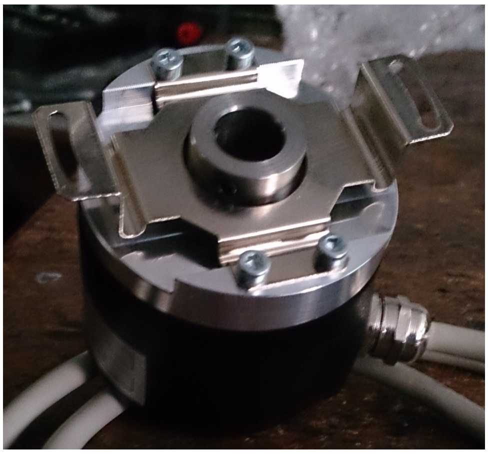


Figure 2.11: LARM magnetic incremental encoder (MIRC 325/64 PB)

frequency does not place a limit on the system. The controller also has a software limit of 8000 rpm [34] which perfectly matches the motor specification.

$$\begin{aligned} ElectricalMaxRPM &= \frac{300(Hz)\times 60(s.min^{-1})\times 2(cycles.revolution^{-1})}{2(Poles)} \\ &= 18000rpm \end{aligned} \tag{2.9}$$

2.10.3 Throttle

A hall effect sensor is used for the throttle. This was purchased as a standard device from EV Works (product number: CTL-EVW-TBX-HALL) [4]. The throttle is powered from pin 26 and 7 and uses pin 16 as the variable, 0-5V, input to the controller.

2.10.4 Controller Programming

The Curtis 1238 is fully programmable with a host of predetermined parameters. Each parameter is described in detail in pages 23-63 of the manual [34]. The controller uses a modified RS-232 serial interface [41] for the connection between the controller and the PC. The interface uses TTL levels [42] and a simple two wire send and receive system. Curtis has then further modified the TTL standard by inverting the logic levels. Figure 3 in Appendix B shows the circuity required to make the connection. This circuit utilises a USB to Serial converter based of the Prolific PL-2303HX controller [43] and a HD74LS04 [44] chip for inverting the TTL signals. The setup process is described in detail in Appendix F.

The controller PC connection can be used for controller set-up including configuring the inputs and outputs outlined above and specifying the type of throttle used. The initial set-up and motor characterisation procedure is attached as Appendix G. This tuning procedure must be run after the RevSki's construction phase has been completed.

2.10.5 Controller Efficiency

The controller is rated as being 95% efficient [34]. The lost power is converted by the internal components to heat. At a full load of 650 amps this equates up to 3 kW of heating. This excess heat is dissipated using first an aluminium plate and secondly a water cooling system. This system is integrated with the motor cooling loop and utilising the existing petrol motors heat exchanger [22].

2.11 Charging

Once depleted the RevSki batteries must be charged in situ. Charging is carried out by a 'GWL/Power Charger' (POW96V25A) [45]. The charger is designed to charge LiFePO4 battery cells at a nominal voltage of 96V. The charger has a constant output current of 25A whilst charging, thus it would take approximately 3 hours to fully charge the battery pack. The charger is fully protected against short circuits, open circuits and overheating. Several chargers were considered and Appendix H gives an overview of this selection process.

As the charger weighs approximately 10kg it was decided not to mount the charger inside the RevSki which keeps the weight of the RevSki as low as possible. Therefore the charger must be manually connected for charging. The RevSki uses an Anderson type high current connector for this. The connector is stored in a waterproof box inside the RevSki's main compartment for the charging connection. This box includes a door switch that integrates with the safety subsystem and prevents operation of the motor whilst charging is in progress. The safety system also provides feedback to the charger to prevent charging when an unsafe condition is detected.

Some companies are working on modular battery systems that will allow the end user to have several batteries that they can swap out when one is depleted [46]. The user can then charge one battery whilst using the other, greatly improving the vehicles usable time. Unfortunately, the limited internal space of the RevSki prevents this option from being incorporated into the main design. However, this presents an area for further investigation and possible future works.

2.12 Drive Train Design: Conclusion

The drive train includes the charging system, battery system, motor control systems, motor and wiring. All aspects of the drive train were designed with safety and power as the main considerations. Most components were purchased off the shelf, this includes the batteries, BMS system, charger, DC-DC converter and motor controller. The motor was constructed by SME to the specification set out by the RevSki team.

It was the author's responsibility to select and analyse each component, ensuring that each section would meet the RevSki design standards. Additionally, the wiring system had to be designed to bring the individual components together maintaining the highest level of safety.

The wiring system includes both hard and soft cut offs, emergency disconnects and fuses to make the system as safe as possible. Feedback is then provided back to the rider with information such as battery state of charge and remaining power. A 12V power system is included for powering the auxiliary components.

Overall the drive system incorporates; 230 headway 38120 LifePO4 battery cells [1], a custom designed fully submersible, water cooled, AC induction motor capable of 50kw continuous power, a Curtis 1238 AC motor controller that is fully programmable, custom 2-stage safety system, a GWL/Power Charger capable of 25A charging current and a custom wiring system. This gives the RevSki drive train the following key specifications:

- Battery pack voltage of 96V
- Battery pack capacity of 80ah/7.68 kWh
- Charging power of 2.4kW
- A continuous output power of 20kW
- A peak output power 60kW
- An overall efficiency of 80% at 50kW
- A charge time of approximately 3.5 hours

Chapter 3

Technology Selections

3.1 Technology Selections: Introduction

Any design project requires the use of outside technologies, which allows the design team to build upon previous knowledge thus facilitating, more exciting developments over time. If this were not the case our engineering knowledge would be limited to what any single individual can learn, as discussed by Scardamalia and Bereiter in "Knowledge building: Theory, pedagogy, and technology" [47]. It is however important to have working understanding of the available choices, so that the best product for the applied use can be chosen.

This project is no different in that it was developed by building on previous knowledge and research. This section will focus on the various technologies required for each component of the electronic drive system. It particular, it will identify the different choices considered and outline which technology was chosen and why. The three most important considerations for the RevSki components have been identified as weight, price and performance. Weight is of great importance as the RevSki is a performance vehicle [11], where power to weight ratio is paramount. Owing to the nature of the budget constraints for the RevSki project, price is a major factor in the choice of components. As the RevSki is a prototype with the aim of showing that the modern principles of a renewable energy vehicle can be applied to a high performance water craft, it is also important for the RevSki to demonstrate that it is cost competitive with existing jet-skis. Finally, the performance of each component must be considered.

The author identified the main components in the electric drive system to be the Batteries, Motor and Controller. Full details the of drive system design are covered in Section 2.3.

3.2 Technology Selections: Literature Review

With high performance electric cars available for purchase since 2008 [8], literature on technology selection in electric high performance electric vehicles is becoming more prevalent both in the form of information for enthusiasts and scientific writing. As the RevSki is a practical project all forms of literature are worthy of consideration.

Examples of enthusiast advice include personal blogs by experienced individuals, such as MetricMind CEO Victor Tikhonov, whose blog gives accounts of his various vehicle conversions, including a high performance Audi conversion. [24] Advice from people experienced in similar projects is vital in preventing the RevSki from repeating the mistakes of others and providing real world solutions to common problems. However, these pieces of literature represent the opinions of single individuals, and do not represent scientific research.

More scholarly articles include "Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles" [48]. These articles allow the RevTeam to base vital decisions on a combination of scientific evidence and industry experts.

This section will summarise key literature relevant to each of the major components for the jet ski's electric drive system.

3.2.1 Batteries

Victor Tikhonov [24] states that the most important characteristics for the battery system in an electric car conversion are:

> *"Economics aside, let's compare the most important parameters relevant for your EV. Fundamentally, what do you want from your battery?*
>
> - *Move your EV far enough (whatever YOUR definition of "far enough" is).*
> - *Be powerful enough*
> - *Able to get charged fast.*
> - *Last long time ("long" means as close to the live of the vehicle itself as possible, ideally 10 years or so).*
> - *Be safe*
> - *Be physically light and small*

- *Be maintenance free (install and forget)*
- *Be a commodity (readily available from multiple sources)*
- *Provide sense of confidence in its performance, typically based on reputation which in turn is based on someone else's previous experiences,*
- *Be cheap*
- *Be cheap*
- *Be cheap*

> *Last three points contradict (and always will contradict) all other points. But don't flip this priority list up side down - your EV won't get very far."* [24]

In order to meet as many of these points as possible, Tikhonov concluded that LiFePO4 was the most appropriate choice.

Studies by qualified engineers have shown the use of lithium batteries to be favourable to lead acid type batteries. Lithium batteries are showen to out perform Lead Acid and Nickel based batteries in performance (W/kg, Wh/kg) but have stricter safety requirements [49], [39].

First used in 1996 [50], LiFePO4 is a lithium based battery technology that solves many existing safety problems with Lithium ion batteries [51]. Abo-Elyousr et. al. [52] discuss the performance of LiFePO4 over previous lithium technologies. Li et. al. [53]discuss the problems of Lithium-ion Batteries, specifically the discuss the safety benefits of LiFePO4. They were able to demonstrate that the LiFePO4 battery technology was more stable especially at higher temperatures often associated with battery packs under high load.

Tan and Tiwari [54] discuss several emerging battery technologies including LiCo which has been shown to have higher power performance than LiFePO4, but less stability, leading to safety concerns owing to a likelihood for thermal runaway. LiCo batteries are often used in smaller applications such as Cell-Phones where the dangers of high heat are less of an issue.

Linden's Handbook of Batteries [5] provides a comprehensive guide to a variety of battery technologies, including, the types considered in this study. Most recently updated in 2011, this book includes both new and experimental battery technologies as well as older, tested technologies.

Although the performance and safety benefits of LiFePO4 are widely proven it is still to be determined which technology is best suited to an electric jet ski. Keeping in mind that not only must performance and safety be considered but also cost which is a significant consideration for the RevSki project. This chapter will compare and evaluate commercially available technologies focusing on which is most applicable to the RevSki.

3.2.2 Motor

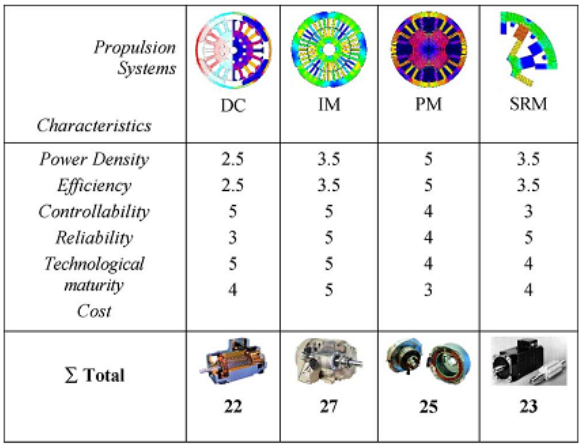
The motor forms the power house of the electric vehicle. It is the component the converts stored electrical potential energy into kinetic energy. Emadi et. al. [48] discuss the importance of choosing and designing the best drive configuration for the success of an electric vehicle project.

There has been an extensive body of research already conducted into the optimal motor design for electric vehicles. Books such as 'Build Your Own Electric Vehicle' by Bob Brant [17], have been available since the early 90's. These books aim to introduce electric cars to the DIY market, showing individuals how easy it is to modify your existing car to be electric powered. This book and other similar books give considerable advice on obtaining the parts for an electric vehicle drive system. Brant suggests that a DC motor would be optimal as they are generally simpler to set up however, he also mentions the performance gains of various AC motor configurations and states that as the cost of AC systems declines, their desirability for electric vehicle conversion will increase.

Around the same time as Brant's book was published, academics were also conducting research into the best technologies for electric drive systems. L. Chang from University of New Brunswick [55] wrote an extensive review of different AC drive systems focusing on their application for electric vehicles. Chang considers IM and SRM AC drive systems with BDCM drive systems. Chang writes that AC motors are better suited to electric drive systems due to superior power, reliability and controllability. IM motors are considered by experts to be the best option for electric vehicles owing to the low cost compared to other motor types.

Since the early 90's there have been significant advancements in motor technology and a reduction in the production costs of more exotic motor types thus it is important to constantly update technological recommendations for a project. A 2006 study by Zeraoulia et. al. [2] again compares various electric drive systems including DC, IM , BDCM and SRM. They focus on the use of motors in hybrid electric vehicles, that is electric vehicles that consist of both an electric and a petrol drive system. While the RevSki is not a HEV it shares the same considerations to HEVs when considering the design requiments for the electric motor. In their study Zeraoulia et. al. considered;

Power Density, Efficiency, Controllability, Reliability, Technological maturity and Cost in the their analysis of the various motor technologies. Figure 3.2.2 shows an overview of these comparisons. Like Chang [55] they found the IM motors offer the best balance of features and cost.



Propulsion Systems / *Characteristics*	DC	IM	PM	SRM
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Σ Total	**22**	**27**	**25**	**23**

Figure 3.1: Electric-Propulsion System Evaluation. Image from Zeraoulia et. al. [2]

Like Zeraoulia et. al. [2], Xue et. al. [56] discuss the choice of motor type for an electric vehicle conversion ,however they found that SRM's are the optimum for electric vehicles. They argue that SRM's have a better power to weight ratio, that the performance gains offsets the slightly lower efficiency of SRM's compared to IM systems. They also state that the cost of SRM's is currently decreasing making them an ideal solution in the future. In addition, they claim that SRM's have improved cooling systems, thus improving their overall safety, which is a key factor in any design consideration.

As with any design decision it is important to understand the components with which one will be working with. The book 'Handbook of Electric Motors' by Toliyat and Kliman[28], published in 2010 is a comprehensive guide to all types of electric motors. While the book itself will not answer the question of which motor is the best solution to a problem, the book provides a deep insight to the workings of each motor type.

While the RevSki shares most of the same requirements as any high performance electric vehicle project, the RevSki introduces a new requirement for motor design, the RevSki must be resilient to water and be capable of cooling in a low airflow environment. Brown et. al. [57] demonstrates the application of a fully submersible electric motor. The design incorporates a lower power (7.5kw) IM drive system. They show that an IM system is capable of operating whilst fully submerged. This is of great importance to the RevSki, as the location of the motor will be low down inside the jet ski where the possibility of water around the motor is very high. Brown et. al. also demonstrate that water surrounding the submersed motor can be effectively used to cool the motor during operation.

The bulk of available literature for electric vehicle motor choice suggests that the IM AC motors ([2], [55]) are the most suitable, however some studies ([56]) suggest the SRM's are improving and may become the suitable choice for some EV applications. It is also shown the IM systems can be operated when fully submersed in water ([57]), which is of particular importance in the context of the RevSki Project.

3.3 Batteries Selection

The battery system is one of the most crucial components in an electric vehicle conversion. The batteries do not simply act as a replacement for the fuel tank, working solely as energy storage, they can also govern the peak power output of the system, thus it is important to balance storage density against power output when choosing a battery system. For the RevSki there is also the need to balance performance against the cost of the systems owing to the budget constraints placed on the project. As shown by previous studies [49], [39] Lithium Ion battery systems are considered the most suitable batteries for electric vehicle systems. However for this study NiMH and lead acid batteries were still evaluated to provide a comparison.

Batteries were only selected for comparison where it was possible to obtain reliable pricing and delivery within Australia. This decision was made because of the practical nature of the RevSki project.

3.3.1 Lead Acid

Lead Acid batteries are a staple of the car industry and are found in most cars. In a normal petrol car they provide high current for short periods to the starter motor then are only required to provide low power levels to the car's auxiliary systems. As of 2008 lead acid batteries represented 70% of the world market for secondary batteries [58].

Lead Acid batteries have the advantage of being easily available and physically very robust. However they suffer from considerably lower energy densities when compared with the modern battery types [5]. Given the requirement of the RevSki to be high performance, ie high power and low weight, lead acid batteries are not an attractive option.

The Lead Acid batteries used in this comparison are the Trojan T1275 battery [59], this is a battery the has been recommended by electric vehicle enthusiasts and is often used in electric golf carts and forklifts. This battery is a 12V, 120 amp-hour battery available for purchased from Go Batteries.

3.3.2 Lithium Ion

Lithium Ion batteries refer to a group of batteries that use exchange of lithium ions (Li^+) as medium for electric charge flow. As the battery is charged or discharged Li^+ ions are transferred between the electrodes. The positive electrode tends to be made from a metal oxide while the negative electrode is made from copper coated in layers of graphite. Positive electrode materials include LiFePO4, LiCoO2 and many others. For this project only LiFePO4 and LiCoO2 batteries were considered.

In general, Lithium Ion batteries have some significant advantages over other battery types specifically in energy performance, energy density and shelf life. Table 3.1 shows the major advantages and disadvantages of lithium Ion batteries. One major disadvantage is the requirement for a complex battery management system. Lithium Ion batteries can become extremely unstable if the voltage of a single cell either drops to low or is charged to high. Therefore, the battery pack must have a system in place to detect these conditions and prevent further operation of the batteries. This adds complexity and cost to any design involving Lithium ion batteries.

LiFePO4

LiFePO4 batteries are a form of Lithium Ion battery that uses Lithium iron phosphate as the material for the cathode. They are noted as having lower performance than LiCoO2 but longer shelf lives and are safer to operate. These positives characteristics that are important in electric vehicles.

LiFePO4 was identified as the best current battery for electric vehicle conversions by [24], [59], [49] and [39] so was an obvious choice for the RevTeam to consider. LiFeP04 is considered an attractive option because it has a high power and energy density whilst employing considerable safety improvements [51] over other Lithium Ion battery technologies. Appendix I includes the MSDS for LiFePO4 batteries, which shows that while safer than some other technologies, LiFePO4 batteries must still be handled with caution.

Table 3.1: Pros and Cons of Lithium Ion Batteries, copied from [5]

Advantages	Disadvantages
Sealed cells; no maintenance required	Moderate initial cost
Long cycle life	Degrades at high temperature
Broad temperature range of operation	Need for protective circuitry
Long shelf life	Capacity loss and potential for thermal runaway when overcharged.
Low self-discharge rate	Possible venting and possible thermal runaway when crushed
Rapid charge capability	May become unsafe if rapidly charged at low temperatures ($< 0°C$)
High-rate and high-power discharge capability	
High coulombic and energy efficiency	
High specific energy and energy density	
No memory effect	
Many possible chemistries offer design flexibility	
Can be made in aluminized plastic cases as "pouch" or polymer cells	

For this comparison a LiFePO4 battery, manufactured by HEADWAY-HEADQUARTERS, LLC [1] and sold by EV Works, Australia [4] was selected. The particulay battery compared is the Headway 38120 which is a single cell (3.2V) LiFePO4 battery rated 10Ah.

LiCoO2

LiCoO2 batteries were the second form of Lithium Ion battery considered by the RevTeam. Lithium cobalt oxide is used as the main material for the cathode. LiCoO2 batteries have been around for longer that LiFePO4 thus representing a more mature technology. They are considered to have higher energy storage levels than LiFePO4 but are not as safe to operate. Even though LiCoO2 is not the recommended battery of electric vehicle conversions, members of the RevTeam agreed it was important to consider an alternative technology alongside LiFePO4.

The battery considered is the Turnigy nano-tech battery sold by HobbyKing [60] (http://www.hobbyking.com). The battery comes in a variety of formats and cell configurations, however, each configuration still has the same basic properties. Normally used in smaller operations such of remote control car's, it would still be possible to wire many of these batteries together to form a larger pack as required by the RevSki.

3.3.3 Battery Comparison

For the comparison of the batteries the author considered several key performance areas as outlined below. It is important to note that these are only figures obtained from manufacturers' specification sheets and have not been confirmed by the RevSki Team. With more time and a higher budget it would be possible to buy a single cell of each battery type and devise some test that would give a more accurate picture for each battery type. The prices used were obtained on-line at the time of the analysis (March, 2013) in Australian dollars.

kW/kg and kW/$

Kilo watts (kW) is the peak power output of the battery. There are two different measurements used for peak power; continuous and instantaneous. Continuous measurements are the power the battery is capable of over a long period of time (greater than 10 minutes). Instantaneous measurements are always higher than continuous measurements, as this represents the peak spike in power over a short period of time. Unfortunately, there is no consistency between manufacturers as to how short a period can be used to measure instantaneous power, which makes instantaneous power measurements a rough guide only.

The kilo watt output of the batteries will directly relate to the acceleration and top speed of the RevSki. As a performance vehicle, both acceleration and top speed is important ,thus kilo Watt's are important. The author compared the kilo watt ratings of each battery to the battery's weight and cost. Weight is important to the RevSki as every extra kilogram will negatively effect performance. Cost is important owing to the restrictive nature of university budgets. Cost is also important to consider when comparing an Electric Jetski to conventional petrol powered jet skis. A lower cost will make an electric jet ski a more affordable option and increase the potential market size, making it a more viable product.

kWh/kg and kWh/$

Kilo watt hours represent the amount of energy stored in the battery. This can be difficult to measure as the efficiency of batteries varies depending on how quickly power is drained from the battery. Generally the higher the power drain, the worse the efficiency of the battery, thus the battery system will measured with a lower kWh. There is no defined way for manufacturers to measure this, unless stated otherwise, the value given is most likely the highest possible value that the manufacturers could measure.

A higher kWh rating directly relates to runtime, so a higher kWh battery pack would allow the RevSki to run for longer. Given that the RevSki is a prototype designed to test if electric jet skis are a viable alternative to petrol jet skis, the RevSki's run time is not as important as peak power. However, for a commercial electric jet ski runtime will be an important parameter. Like kW rating, the author compared kWh's with weight and cost.

Life cycles

Vehicle life times are measured in the 10's of years therefore it is expected that the battery packs should be able to keep up. It is well known that this is not the case, as part of the service cost, an electric vehicle will require replacement battery pack at some point in the vehicle's life The longer between battery pack replacements, the better the service life and the higher the quality of the vehicle as a consumer item. Few manufactures give this sort of information as it is incredibly variable given the different usages of batteries. Generally speaking Lithium Ion, batteries have significantly higher life cycles than Lead acid batteries.

3.3.4 Battery Comparison Conclusions

Tables 3.2 to 3.5 show the results of the comparison for the three batteries considered. Table 3.2 shows the basic parameters for the batteries. Table 3.3 gives the power and energy outputs of the battery as per the manufactures specifications. Table 3.4 and 3.5 give the calculated values for power and energy for each battery compared against price and weight.

The data indicates that the Lead Acid batteries are significantly heavier for both the same energy and power. They are however cheaper per kWh than the other batteries, but the significant difference in kWh/kg and kWh/$ make Lead acid batteries uncompetitive in the modern electric vehicle market. For this reason they were not used in the RevSki.

Competition between the two Lithium Ion batteries LiFePO4 and LiCoO2 is a more closely run race. The values for the kW rating on the Turnigy seem unreasonably high. While it is possible that they are valid measurements, it is the author's belief that the manufacturer is reporting peak values obtained over a fraction of a second rather than minutes. The only way to ensure a valid comparison is to compare the performance of the batteries through direct testing.

Table 3.2: Comparing Lead Acid, LiFePO4 and LiCoO2 batteries, Part A

Battery	Technology	Cost per unit	Weight per unit	Voltage
Trojan	Lead Acid	350	37	12
Headway	LiFePO4	18	0.3	3.2
Turnigy	LiCoO2	19.99	0.201	11.1

Table 3.3: Comparing Lead Acid, LiFePO4 and LiCoO2 batteries, Part B

Battery	Peak Output Continuous (A)	Peak Output Instantaneous (A)	Energy Storage (ah)
Trojan	75	270	90
Headway	30	100	10
Turnigy	22	99	2.2

Table 3.4: Comparing Lead Acid, LiFePO4 and LiCoO2 batteries, Part C

Battery	kW Continuous	kW Instantaneous	kWh	kWh/$	kWh/kg
Trojan	0.9	3.24	1.08	0.003085714	0.029189189
Headway	0.096	0.32	0.032	0.001777778	0.106666667
Turnigy	0.2442	1.0989	0.02442	0.001221611	0.121492537

Table 3.5: Comparing Lead Acid, LiFePO4 and LiCoO2 batteries, Part D

Battery	kW/$ Continuous	kW/kg Continuous	kW/$ Instantaneous	kW/kg Instantaneous
Trojan	0.002571429	0.024324324	0.009257143	0.087567568
Headway	0.005333333	0.32	0.017777778	1.066666667
Turnigy	0.012216108	1.214925373	0.054972486	5.467164179

The increased safety of the LifePO4 cells [51] is a major factor in the decision. The RevSki is a harsh environment for the batteries, they will be subject to intensive use and high impact forces and as such they must be very stable under a variety of conditions.

The LifePO4 performed significantly better than the Lead Acid batteries and have been shown to have a higher level of safety over the LiCoO2 batteries. Therefore LifePO4 are the best choice for the RevSki.

For these reasons the RevTeam decided to use the 38120 LifePO4 manufactured by HEADWAY-HEADQUARTERS, LLC [1] and sold by EV Works, Australia (http://www.evworks.com.au).

3.4 Motor Selection

As discussed by Emadi et. al. [48], the motor rates as one of the most important parts of an electric vehicle. The motor is responsible for converting electric energy to kinetic energy. It does this by exploiting principles of electromagnetism. In the RevSki the motor will be connected directly to the impeller, which will pump water from under the jet-ski to the rear providing forward motion. Reverse motion is gained by the use of a flap over the output of the impeller [61]. The jet-ski has no other method for breaking. Therefore features such as active or regenerative breaking are of no benefit to the RevSki application.

As part of the technology choice for the RevSki, two competing types of motors design were considered. Similar to the battery choice, only products that are commercially available were considered. In addition, only established motor technologies were considered, to ensure the practical success of the project. For this study the author considered a series wound DC motor and an Induction AC motor.

3.4.1 Series Wound DC motor

Series wound DC motors are a long established DC motor technology that has been used extensively in the DIY electric car scene. [62] This technology comes recommended by several online guides including Brant's book on electric vehicle conversion [17]. The motor chosen for further investigation is the NetGain WarP 11 DC motor. This motor is available for purchase from EV Works in Perth, Australia (http://www.evworks.com.au) and is recommended by the team at EV works as the best DC motor available. Figure 3.4.1 shows the torque curves for the motor. Note that this test was run at a lower voltage

(76V) than the RevSki is planned to run at (96V), however the motor is also rated for use at 96V, thus the motor would have a higher power output in the RevSki system than represented by the graph.

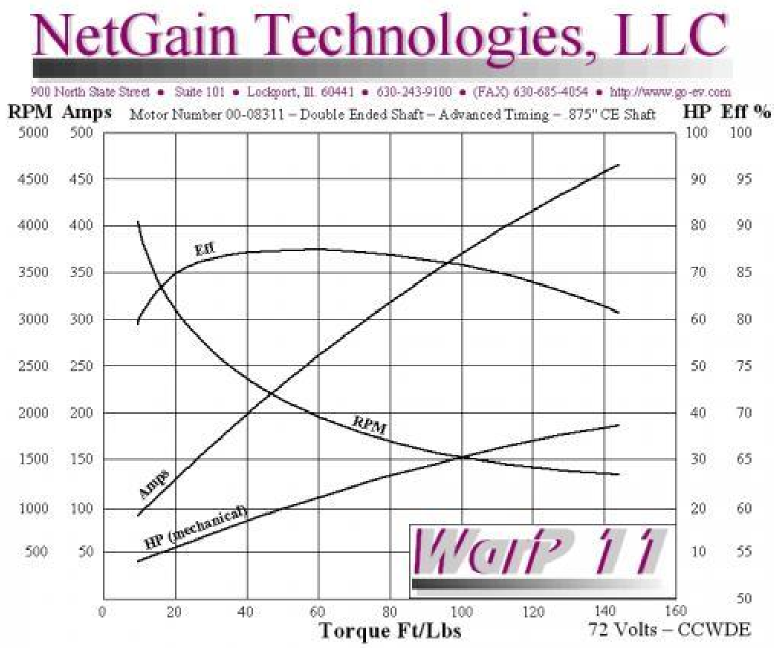


Figure 3.2: NetGain WarP 11 DC motor. Image from Go-EV [3]

The series wound motor is a DC motor, which is advantageous because the power in the jet ski comes from the batteries that operate as DC devices, so there is no need for an inverter. A series wound motor has the field windings in series with the armature, this has the advantage that the motor is capable of providing close to maximum torque at 0 rpm [28]. This is very usefully in automotive applications as it removes the need for a clutch and gives great starting acceleration.

The control systems for DC motors in an electric vehicle application are significantly simpler than the control systems for AC motor as the current from the battery only needs to be modulated using pulse width modulation, meaning there is no requirement for an inverter. Because a commutator is required, the motor may suffer from greater problems with ongoing reliability and will be harder to fully water proof.

3.4.2 Induction AC

Induction motors are considered to be one of the optimal motor designs for electric vehicle ([55] and [2]). The IM system considered here is the HPEVS AC-51 system available from EV works in Perth, Australia [4]. This motor is designed for a peak output of 65kW. Figure 3.4.2 shows the torque curves for this motor at 144V. As the motor would be a lower voltage (96V) in the RevSki it is expected that the peak power output be slightly lower.

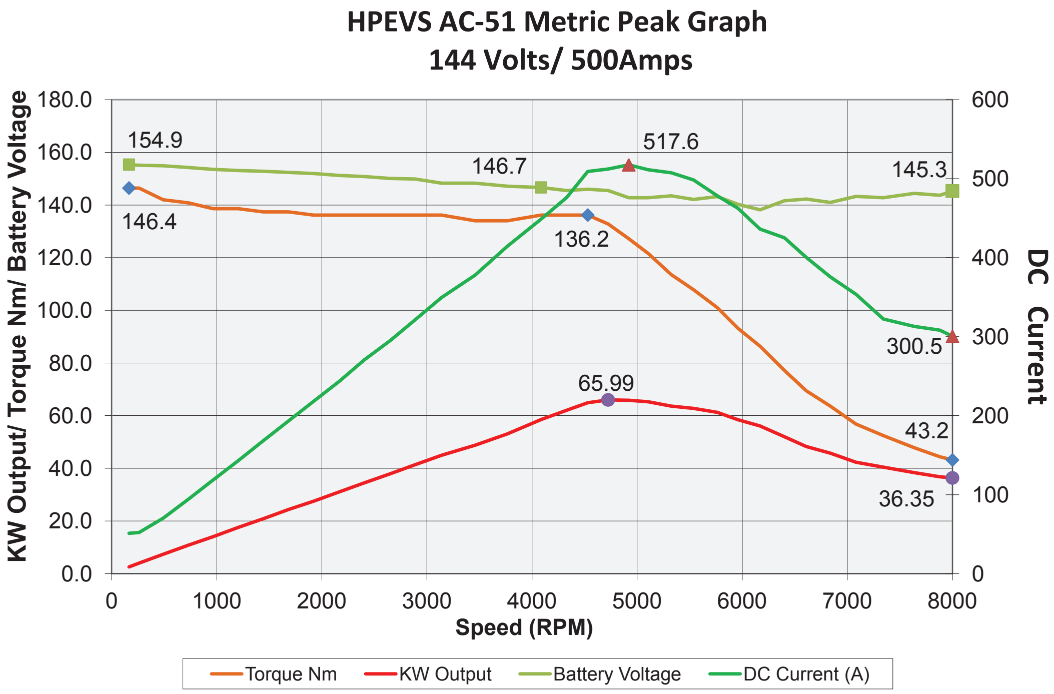


Figure 3.3: HPEVS AC-51 Motor. Image From EV Works [4]

An induction motor works by transferring power to internal windings on the rotor using the principle of induction thus removing the need for a direct connect and commutator. The downside is that the motor must be powered by AC. In an electric vehicle application where power is supplied from a battery bank this means an inverter is required to turn the DC power from the battery into AC power for the motor. The type of induction motor being considered for the RevSki is a 3 phase induction motor. Poly phase induction motors are more efficient than their single phase counter parts [28]. However, providing 3 phase power and controlling the motor requires a more sophisticated controller, adding to the complexity and cost of the system.

Induction motors are more efficient than series wound DC motors and have less moving parts making them potentially more reliable. AC motors however require sophisticated controllers in electronic vehicle applications. They also have the advantage of being easier to water proof [57] which is ideal for the RevSki. AC motors have the added advantage of being more efficient at implementing regenerative breaking, however this is of no relevance to the RevSki so it will not be considered as either a benefit or a disadvantage.

3.4.3 Motor Comparison

For the comparison of the two motors, several key performance areas were identified. Each motor was then evaluated for each key performance area to establish a final performance result. As the RevSki team does not have the budget to purchase and test motors, the values for the comparison have to be taken from manufacturers specification sheets and available material. Thus it is important to note that these figures will represent a 'best case situation' and the real world application of the RevSki performance might be very different.

Price

As with all parts of the RevSki project it is important to minimise costs. This is required to fit within the practical requirements of the Rev Team's budget and in demonstrating the economic viability of an electric jet ski. When comparing the price of the two motors it is important to consider the cost of the required controller. For the AC-51 IM system this was already included in the quoted price. For the WarP motor the 'ZEVA MC600S' DC motor controller is a suitable controller and represents an expected price for controlling the WarP motor. This controller is also available from EV Works.

Peak Power

The RevSki is a high performance electric vehicle, thus for the RevSki to be successful the motor must have a high output power. When comparing the torque characteristics of the two motors, high starting torque is of lower importance than peak power due to the performance characteristics of light water craft.

Weight

The weight of the drive system is also of great importance as this will have a direct impact on the performance of the Rev-Sk. Every extra kilogram negatively impacts on overall performance.

Peak RPM

The existing motor removed from the RevSki was rated for a high 8000 rpm [61] drive system, in order to match performance as much as possible with the existing jet ski the motor must be able to reach as close to 8000 rpm as possible. However, even if the motor were capable of higher rpm's it would need to be electronically limited to protect the impeller. For motors where the peak rpm does not match the peak rpm of the impeller a gear box could be used to match the system, however this would add increased complexity, weight and cost.

Table 3.6: Comparison of AC-51 and Warp 11 Motors

	AC-51	WarP 11
Cost, including controller	$6150 AUD	$5290 AUD
Weight	60KG	105KG
Peak Power, Adjusted for 96V	65 KW	38 KW
RPM	8000	4000
kW/kg	1.083333333	0.361904762
kW/$	0.010569106	0.007183365

3.4.4 Motor Comparison Conclusions

Table 3.6 shows the results of the comparison of the IM system utilising the AC-51 motor and the DC system utilising the WarP 11 Motor [4]. From this table it is clear to see that although the AC-51 is more expensive it represents a much higher power to weight ratio and a higher power to cost ratio than the WarP 11. This backs up the conclusions of other research papers, that induction motors represent the current best choice of motor for electric vehicles.

The two other highly important specialist requirements for the RevSki motor are water proofing and cooling. As was discussed by Brown et. al. [57] both of these problems can be solved with a submersible motor. After deciding the IM was the best technology for the RevSki it was decided the submersible motors should also be investigated. The AC-51 is not a submersible motor design, however, the RevTeam was however fortunate to have the assistance of a Perth based motor design company, Submersible Motor Engineering Pty Ltd (SME). With the assistance of the RevTeam SME, were able to design and construct a fully submersible induction motor that utilises water cooling.

The most suitable electric motor for the RevSki is a fully submersible and water cooled induction AC motor. This motor offers a high performance for a comparable price and satisfies the two special requirements of water proofing and cooling required by the unique nature of the RevSki electric vehicle.

3.5 Controller Selection

In an electric vehicle the motor controller is responsible for transferring power from the battery pack into the motor. The controller must also be capable of controlling the motor speed based on a combination of inputs such as the throttle. As well as speed control, the controller is also responsible for safety systems, such as shutting down power to the motor in cases of extreme temperature. [17] For the RevSki it was chosen to go with a 3 phase Induction motor (see Section 3.4) for this case the controller has the added job of converting DC power into AC power.

For the selection a suitable motor controller, the following key design parameters must be met in order for the controller to be compatible with the goals of the RevSki.

- Work with a voltage of 96V.
- Be high power (greater than 500amps).
- Be compatible with the three phase induction motor, being developed by SME.
- At least IP65 water proofing
- Be of appropriately high safety standards.

As the design and implementation of an AC motor controller is beyond the scope of this project and not required for answering the question, 'Is an electric jet ski a viable alternative to petrol powered jet skis?' it was decided by the RevTeam to purchase a commercially available controller. Curtis Instruments make controllers dedicated to electric vehicle operations and their 1238-76XX controller satisfies all of the requirements for the RevSki. The Curtis controller is capable of 600amps for a 2min period and is a fully programmable AC controller with a IP65 environmental rating. In addition the controller all so satisfies EMC design requirement EN12895 and Safety design requirement EN1175. [63]

3.6 Technology Selections: Conclusion

Every modern design project is built on the technologies and improvements of other projects. The saying goes, 'There is no point in re-inventing the wheel.' The goal of the RevSki is to answer the question 'Is an electric jet ski a viable alternative to petrol powered jet skis? In order to answer this question effectively, the team choose to research and purchase commercially available components for the construction of the RevSki. This chapter outlines the major technology decisions made in designing the electric drive train for the RevSki, covering the selection of battery, motor and controller.

For the batteries it was shown that the LiFePO4 technology was the best candidate for the RevSki. These batteries offered the best power to weight and cost to weight ratios whilst maintaining a high level of safety. The chosen battery is the 38120 LifePO4 manufactured by HEADWAY-HEADQUARTERS, LLC [1].

After considering both series wound DC motors and induction AC motors for the RevSki it was found that the IM offered the best performance and had the important advantage of waterproofing. The motor used in the RevSki was designed and built by Submersible Motor Engineering Pty Ltd (SME) in consultation with the RevTeam.

The disadvantage of an AC motor like the motor provided by SME is the increased complexity of the controller. This was solved with the commercially available Curtis 1238-76XX.

Chapter 4

Performance Test Design

4.1 Performance Test Design: Introduction

The goal of the RevSki project is to determine if an electric jet ski is a viable product. The first step is to determine if the RevSki can be competitive with a petrol jet ski in a number of key areas. As there is no definitive guide to performance testing of jet skis it is the responsibility of the RevSki Team to devise an appropriate testing procedure for the RevSki.

It is the author's recommendation that further research be done in this area before testing begins. This includes, interviewing members of the various communities involved with the use of jet skis. This will allow targeted testing focusing on the areas of performance that are important to members of these communities.

This chapter does not reflect the final view of the Rev Team, only the author's recommendations to the Rev Team for testing procedure.

4.2 Performance Test Design: Literature Review

Academic material on performance testing of jet skis is limited. Information on the range testing of electric vehicles is available, however this is not applicable owing to the different nature of water craft over road craft. Thus, it is up to the Rev Team to devise appropriate tests.

Hazuku et. al. carried out testing for their boat "RAICHO-S" [29]. They tested the basic statistics of top speed and runtime at both 10kn (full speed) and 6kn. At 10kn the boat was able to run for 45 minutes, by almost halving the speed they were able to boost the run time by over 200% to 150 minutes. They also conducted extensive testing on noise levels, they used an equivalent petrol powered vessel of similar size and performance to provide a baseline and tested noise levels at several distances and speeds. They showed that the "RAUCGO-S" produced significantly less noise than the petrol test boat. Testing undertaken with the RevSki will aim to replicate this result.

The use of buyers guides such as "popular mechanics" [64] and "PWC offshore racing" [65] serve as a starting point in determining what the average potential jet ski owner may be expecting from a personal water craft. The author proposes to interview people who work with jet skis daily, such as a jet ski hire operator and a surf life saving organisation.

4.3 Performance Testing Methodology

Testing must be conducted in a safe manner. From Appendix G, rider error was identified as one of the highest risks in the operation of the RevSki. To reduce this risk the following controls are proposed:

1. Every driver must hold a valid Recreational Skippers Ticket in accordance with Western Australian Law [66].

2. A second vessel must be present at all times and able to render assistance.

The above controls if adhered to throughout the testing process will greatly improve the safety of the testing procedure.

Throughout the testing, a second jet ski will be used in ordered to be able to make comparable assessments of the RevSki's performance. This second jet ski will be a petrol powered jet ski of similar size to the RevSki and similar power to the donor jet ski (130hp [61]). For the rest of the section this will be referred to as the TestSki.

The tests are separated into two sections. First the 'Base Tests' will look aim to collect raw data on both the RevSki and the TestSki. These tests are used to determine the RevSki's effectiveness for a range of applications and providing a base comparison between the two jet ski's.

Next tests will be devised to test both the RevSki and the test Ski in a variety of real world applications. These tests will be designed to find any flaws in the RevSki and demonstrate if an electric jet ski is competitive compared with an existing jet ski.

The RevSki is a prototype product and it is unrealistic to expect it to compete across all performance areas. These tests are designed to find which areas the RevSki can compete in and identify which areas need to be improved before the RevSki can be considered commercially competitive.

In order to provide informative tests, each test should be repeatable and should be repeated at least three times so an average result can be used.

4.4 Base Tests

4.4.1 Acceleration

As a performance vehicle, acceleration is an important parameter. Acceleration tests should be carried out under a variety of conditions and speeds. By testing at a variety of speeds and conditions the performance characteristics of the jet ski can be analysed for a range of applications. The author proposes a combination of the following:

- Conditions:
  - Rough weather
  - Smooth weather
  - Acceleration into wind
  - Acceleration away from the wind.
- Speeds
  - Standing Start to medium speed cruising speed (15 to 20 kn)
  - Standing Start to high speed cruising speed (30-35kn)
  - Slow Start (5-10kn) to medium speed cruising speed (15 to 20 kn)
  - Slow Start (5-10kn) to high speed cruising speed (30-35kn)
  - Fast Start (15-20kn) high speed cruising speed (30-35kn)

The testing process is fairly straight forward. Measurements of the above speeds will be determined using the on-board speed gauge, if operational, or by using a mountable auxiliary speed gauge, then timed using a simple stop watch. An alternative test for acceleration would be a simple drag race which could be held in the above conditions over, 100m, 300m, 500m.

The RevSki's electric motor has very high torque at low RPM's therefore one would expect to see the RevSki accelerate faster at slow speeds. However the TestSki's higher power engine may give it an advantage in accelerating at high speeds.

4.4.2 Cornering

Cornering ability makes for a large part of a jet ski's overall performance and also important for safety and collision avoidance. Tests for cornering ability should be carried out in a variety of conditions and will include minimum turning radius at a variety of speeds.

It is not expected that the cornering ability of the RevSki will have much variation from that of the donor jet ski. However redistribution of weight may have some impact thus it is important to still test this category. It is the author's recommendation that cornering ability be tested with the use of a tight slalom circuit and the assistance of an experienced rider.

4.4.3 Top Speed

Jet skis are often used for cruising, where the top speed of the craft is a crucial statistic. Top speed is also an important parameter for comparing the engine power of the two jet skis. Top speed is primarily limited by four factors; engine power, engine maximum RPM's, impeller design and hull design. Impeller and hull design are unchanged in the RevSki from the donor jet ski, that leaves engine power and maximum RPM as the major factor in the RevSki's top speed.

For testing, the top speed is defined as a 'sustainable top speed', that is, where the jet ski can maintain that speed for at least 5 minutes. This represents a situation such as cruising around the river. Top speed can be tested either using an on-board speed gauge or a GPS and should be tested under a range of conditions.

The RevSki has a top RPM of 8000 which is equivalent to the donor jet ski [61]. The full engine power of the RevSki is only available in bursts so this may limit the continuous top speed.

4.4.4 Run Time

To be commercially viable the RevSki must be able to run long enough to be usable. Run time is measured as the time from full charge to 30% charge remaining. This is to protect the batteries which maybe be damaged owing to over discharging. Run time is affected by three main factors; Energy storage either litres of fuel or kWh of batteries, engine efficiency and riding style.

Remaining power is measured by the 'TBS E-Xpert Pro' [36] and time can be measured by a stop watch. Run time will vary considerably based on usage. Thus testing should record run time in a variety of conditions:

- Consistent speeds: 10kn, 20kn and 30kn
- Varied speeds: starting at 10kn speeding up to 30kn for a 2mins then slowing down, then repeat.

This will allow for different indications of riding style and conditions to leave only the engine efficiency and energy storage as the deciding factors in run time. It is also possible to convert litres of petrol to kwh (Eq 4.1), which will allow for a comparison of the overall efficiencies between the RevSki and the Test Ski.

$$\text{1litre of petrol} = 9.5\text{kwh [67]} \tag{4.1}$$

$$\begin{aligned}\text{RevSki Letres of petrol equivalent} &= \frac{\text{7.68(kwh battery pack)}}{9.5(kwh.l^{-1})} \times \frac{\text{80\% eff of RevSki}}{\text{30\% eff of Test Ski}} \\ &= 2.2L\end{aligned} \tag{4.2}$$

The Test Ski will have a fuel capacity of approximately 50L whilst the RevSki has a equivalent capacity of approximately 2.2L (Eq 4.2). This implies that the TestSki will have a far longer run time. The TestSki is expected to have a fuel efficiency of around 30L per hour [68] , at top speed, which should give the Test ski a run time of about 1.6 hours and the RevSki a run time of 5 minutes. However it is difficult to predict the performance of the electric engine operating in this situation, thus real world testing will determine the real usage statistics.

4.4.5 Ride Comfort

Jet Ski's are regularly considered as recreational vehicles, therefore the comfort and enjoyment of the rider is important to the overall success of the jet ski. There are several factors that contribute to comfort of the rider that may be effected by the electric conversion. This includes noise level, ease of use and engine vibrations.

Noise levels can be measured using a decibel meter and should be measured at several different speeds. Engine vibrations can be measured using an accelerometer and again should be measured at several different speeds. Ease of use must be determined by interviewing riders. Care must be taken to treat both the Test Ski and the RevSki equally in any surveying in order to obtain usable results. A rider survey could also include questions of vibration and noise level to provided a qualitative approach as well.

It is expected that the RevSki will be both quieter and have less vibrations than the Test Ski due to the electric motor. Ease of use should be similar as very little modifications have been made to the rider interface.

4.4.6 Environmental Impact

One of the key aims of the RevSki project has been to build an environmentally friendly jet ski, therefore it is important to quantify any improvements to environmental impact as part of the testing procedure. Areas of impact for a conventional jet ski have been identified as noise, air, and water pollution [13].

Noise pollution can easily be measured using a decibel meter held at various distances to the jet skis at various RPM ranges. Air and water pollution are harder to quantify. The RevSki has no exhaust so there is zero direct air and water pollution. The Test Ski on the other hand has all the pollutants normally associated with petrol engines and liquid exhaust systems.

4.5 Situational tests

After conducting the base tests, the author recommends that it would be beneficial to conduct situational testing. The situational tests will be designed to cover specific use cases for jet skis to determine if the RevSki would be suitable for these applications. Common uses for jet ski's have been identified as water skiing, racing, surf lifesaving and cruising.

In order for these test to be as accurate as possible members of the various different jet ski communities, should be interviewed to determine which features of the jet ski are most important to their specific application. If possible, it would also be preferable to involve members of these communities directly in the testing process to get feedback from experienced riders.

These tests will not only determine which applications are suitable to electric jet skis but also provided an indication of which areas the RevSki can be improved to make the RevSki more competitive with existing jet skis.

4.5.1 Water Skiing

Water skiers and wake boarders regularly use jet skis as the tow boat for their sport. Water skiing requires a fast manoeuvrable boat, with high power to weight ratio.

> The speed of the boat keeps the skier afloat instead of sinking and the ideal boat will be fast and powerful and able to cut through even choppy water with ease. [69]

The RevSki is expected to have very good slow speed acceleration which could be very good for getting the skier out of the water. Once the skier is up on the skis, high engine power isn't as important so the RevSki shouldn't be limited by its lower continuous power.

4.5.2 Racing

Racing is carried out by clubs such as the 'WA Jet Ski Club' (http://www.jetsportwest.asn.au/) who race on the swan river. Racing requires high speeds, fast acceleration and tight cornering. As jet ski racing is a high speed sport, the author recommends contacting the WA club and organising for a experienced rider to assist with the testing the racing ability of the RevSki.

Given that races might be over within the RevSki's limited run time, it is expected the RevSki will be highly competitive in this area.

4.5.3 Surf lifesaving

Jet skis are regularly used by surf lifesavers to assist in their daily duties [12]. This represents a non recreational use and may require vastly different performance from the jet ski than other categories. Surf lifesavers will require the jet ski to perform well in high wave conditions, be very safe and easy to operate. However surf lifesaving operators may require the higher run times that can only be offered by conventional petrol powered jet skis.

4.5.4 Cruising

The cruising category represents a recreational use, where riders use the jet ski to travel from point A to point B. Riders in this category may place a high importance on rider comfort and environmental impact, which are two areas where the RevSki is expected to perform well. However, they may also require a long run time and high top speed which are two areas the RevSki is not expected to perform as well as conventional petrol jet skis.

4.6 Performance Test Design: Conclusion

The goal of the RevSki project is to determine if an environmentally friendly, electric powered jet ski can be developed to be competitive with existing petrol powered jet skis. After construction, a testing and analysis stage must be carried out to answer this question.

The author recommends a two stage testing process. The first stage will involve determining the base statics of the RevSki. This will highlight the strengths and weaknesses of the RevSki in relation to TestSki. After this the RevSki should be tested in a variety of real world situations to find cases where the RevSki is competitive and also to identify features of the RevSki that need improvement to make it competitive in the real world.

Chapter 5

Conclusion

5.1 Project Update

The RevSki project can be broken into 4 stages; Design, Construction, Testing and Analysis. During the course of 2013 the design phase of the RevSki project has been completed. This includes both mechanical and electrical designs. All designs were completed with safety as the number one priority and have where, applicable, been designed to comply with Australian Standards. The construction phase has already begun. All of the major components have been purchased and delivered, including; batteries, the motor, motor controller and miscellaneous parts such as contactors and relays. The jet ski itself has been prepared for construction with all non-essential components removed and has been water proofed, ready for the installation of the electric drive system.

In 2014, the project will see the completion of the construction phase and implementation of the testing and analysis phase. At the end of the process the RevSki Team will be able to answer the question: 'Is an electric Jet Ski competitive with a conventional petrol jet ski?'.

5.2 Completed Work

This thesis has focused on the overall design of the electric drive train and the author's involvement in the RevSki production.

The full wiring system was designed to provide high power electric supply to the motor, integration with a custom designed safety system and 12V power to auxiliary components, this is covered in detail in Section 2. The main components of the drive train consist of 230 Headway 38120 battery cells, a Curtis 1238 AC motor controller and a water cooled 50kW AC induction motor developed by SME. The 12V auxiliary power is provided by a 'HWZ Series DC/DC Converter 96V to 12V 300W'. The batteries are recharged by a 'GWL/Power Charger'. All these combine to give the following total statistics for the RevSki:

- Battery pack voltage of 96V
- Battery pack capacity of 80ah/7.68 kWh
- Charging power of 2.4kw
- A continuous output power of 20kW
- A peak output power 60kW
- An overall efficiency of 80% at 50kW
- A charge time of approximately 3.5 hours

Throughout the design process the author was required to conduct extensive research into the many different components necessary to make the RevSki a success. A summary of this research for the three main components of the drive train, the batteries, the motor and motor controller is provided in Section 3. It was decided to use LiFePO4 batteries and an AC induction motor.

Work has already begun on devising an adequate testing procedure for the RevSki. These tests will be used both to determine the RevSki's base statistics such as maximum acceleration and top speed and then compare these with a conventional petrol powered jet ski. Further to that, situational tests should be devised for the RevSki to determine which real world applications would be suitable for the RevSki. The author's recommendations for testing are outlined in Section 4

5.3 Future Work

Now that the design phase of the RevSki is complete, the construction phase will take priority. Future work will include the construction and will require an electrical engineer to test the various components and safety systems, as they are installed. A mechanical engineer will also be required to oversee the construction to ensure that components are installed in a manner that will allow them to withstand the rigours of the impact forces associated with testing the RevSki.

As well as the continuation of the project there are several other areas for possible future work and improvement on the drive train design, including improving run time and improving the interface for the rider controlling the jet ski.

Run time can be improved potentially, by adding more battery cells. However, this will increase the cost of the project and require the design of a new battery box yet will require little modification to the existing wiring system. This would have the added benefit of improving the efficiency of the battery system although will significantly increase the cost of the RevSki.

An Arduino is already included to provide soft warning levels for the custom designed safety system, these can be expanded to provide greater feedback to the user through an output screen. More sensors could be added to provided estimated remaining run times, remaining distances, measure peak acceleration, top speed and to provide feedback to the race keen rider. There is also a heads up display built into the jet ski that communicates with the existing ECU over CAN Bus. It should be possible to reverse engineer this component and utilise the existing screen for displaying key data to the rider.

5.4 Recommendations

The author recommends that the performance tests be designed in consultation with experienced members of the various communities that involve jet skies around Perth. This is likely to lead to better testing and a more reliable answer to the question: 'Is an electric Jet Ski competitive with a conventional petrol jet ski?'.

As per the attached Risk Analysis, the greatest dangers are water in the battery box and rider error. The author recommends that continuous inspection of the water proofing be carried out before every use. Similarly all riders must be fully qualified to ride PWC as per Western Australian Law and a second vessel PWC or boat should be present to assist should anything go wrong during water testing.

One possible limitation to the continuous performance of the RevSki could be due to overheating. Currently both the motor and the motor controller are water cooled using a closed loop cooling system. However the batteries have no cooling system installed. Air cooling would be possible, however this must be a closed loop system to maintain the waterproof integrity of the battery box. If it is found that cooling of the batteries is required the author recommends small water cooled radiators and fans be placed inside the battery box, with the coolant piped into the main cooling system.

5.5 Final Thoughts

The RevSki is a ground breaking device that will, when successfully completed, be one of the first high performance electric personal water crafts in the world. Throughout the design process the RevSki team was required to overcome several engineering challenges, the most important of which was ensuring that the essential safety standard of the drive system was maintained in the demanding water prone environment. This compelled the RevSki team to work together, utilising the multidisciplinary skills of the RevSki team. It also provided a sound introduction to the formulation and implementation of safety controls and protocols.

The author's involvement with the project has been to oversee the drive train design, select which components to purchase and to ensure that all subsections of the project work efficiently together. The RevSki has been designed to be as safe as possible with multiple fail safe systems put in place to protect the rider and the environment in the case of a component failure or accident.

During the design process several battery and motor technologies were considered to ensure that the most appropriate products were used for the RevSki. The final choice was LiFePO4 batteries and an AC induction motor.

The RevSki has been designed to be a high performance water craft. The fully electric drive system is capable of producing a maximum output of 60kW and a continuous output of 20kW. However the size of the battery pack will be a limiting factor giving the RevSki an approximate running time of 20 minutes at the continuous power of 20kW.

Future works by the team in 2014 will include performance testing of the RevSki and analysis of possible solutions to such limiting factors. The RevSki is a unique project that will contribute to the advancement and knowledge in the field of renewable energy vehicles.

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Appendix A: Risk Assessment Matrix

		Severity				
		Negligible	Marginal	Serious	Critical	Catastrophic
	Chance	1	5	10	15	25
Certain	10	10	50	100	150	250
Likely	6	6	30	60	90	150
Possible	3	3	15	30	45	75
Unlikely	1	1	5	10	15	25
Rare	0.5	0.5	2.5	5	7.5	12.5

Extreme
High
Medium
Low

	Example
Negligible	jet ski stops operation or a fuse has to be replaced
Marginal	Damage to minor components eg sensors and relays
Serious	Minor injury to rider or damage to major components eg motor or batteries
Critical	Major Injury to rider or damage to multiple major components
Catastrophic	Danger to others, complete destruction of the RevSki, Death of rider

				Before				After						
Risk ID	Component/area	Risk	Consequence	Severity	Likelihood	Combined	Engineered Controls	Severity2	Likelihood3	Combined4	Other Controls	Severity23	Likelihood34	Combined45
1	Battery Sytem	Water in battery box (small amount)	possible damage to batteries	10	6	60	Waterproofing battery box. Including silicon on all joins and rubber gromets	10	1	10	On going water testing	10	0.5	5
2	Battery Sytem	Water in battery box (large amount)	Short circuiting of batteries	15	3	45	Waterproofing battery box. Including silicon on all joins and rubber gromets	15	1	15	On going water testing	15	0.5	7.5
3	BMS	Short Circuit	Damage to batteries	10	3	30	Fuses	1	3	3				0
4	Main Wiring	Short Circuit	Server damage to batteries, possible fire	25	6	150	Main fuses and aux fuses, waterproofing	5	3	15	Training for anyone working on the RevSki	5	1	5
5	BMS	general failure	Damage to batteries	10	1	10	Fail safe design	5	1	5				0
6	Main hold	Water bilge small amount	possible damage to components	5	6	30	Waterproofing and shut off sensors	5	1	5				0
7	Main hold	Significant water	damage to circuits and possible short circuiting	15	6	90	Waterproofing and shut off sensors	5	1	5				0
8	Battery System	Overheating	Server damage to batteries, possible fire	25	3	75	Temperaute sensors and cutoffs	5	1	5				0
9	Controller	Overheating	Server damage to controller	10	3	30	Cooling system and built in temperature cutoffs	5	1	5				0
10	Motor	Overheating	Server damage to motor	10	3	30	Cooling system and built in temperature cutoffs	5	1	5				0
11	Controller	Failure of controllers saftey systems	Damage to motor or components	15	1	15	Dual emergancy manual shutoffs	1	1	1				0
12	Safety Subsystem	general failure	Server damage to many compoents, possible fire	25	3	75	Fail safe Desgin and Complete Manual cutoff	5	1	5				0
13	Contactor	Failure in the On position	Server damage to many compoents, possible fire	25	3	75	Fail safe Desgin and Complete Manual cutoff	5	1	5				0
14	Rider	Rider falls off during operation	Out of control RevSki, inability to hit emergancy stop	15	10	150	Deadmans switch	5	1	5				0
15	Rider	Rider falls off during operation	Rider drowns	25	10	250				0	Rider training, Rider must wear lifejacket and not be out on the water alone	5	3	15
16	Cooling system	general failure	Overheating of controller and motor	10	3	30	Controller and motor have temperatue shutoffs	5	1	5				0

Appendix B: Wiring

Figure 1: Full Rev Ski Wiring Diagram

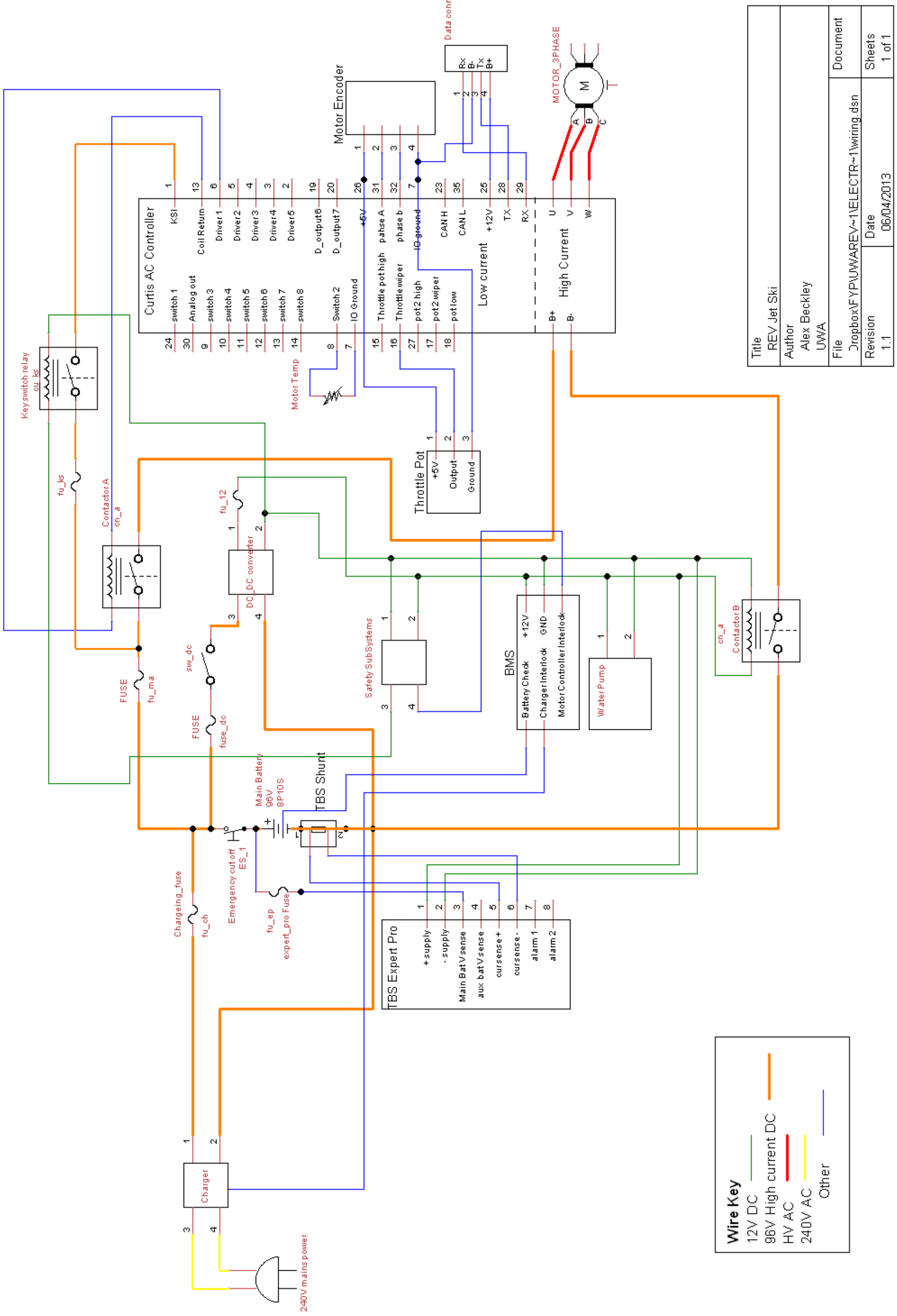


Figure 2: Breakout of all connectors for Curtis Controller

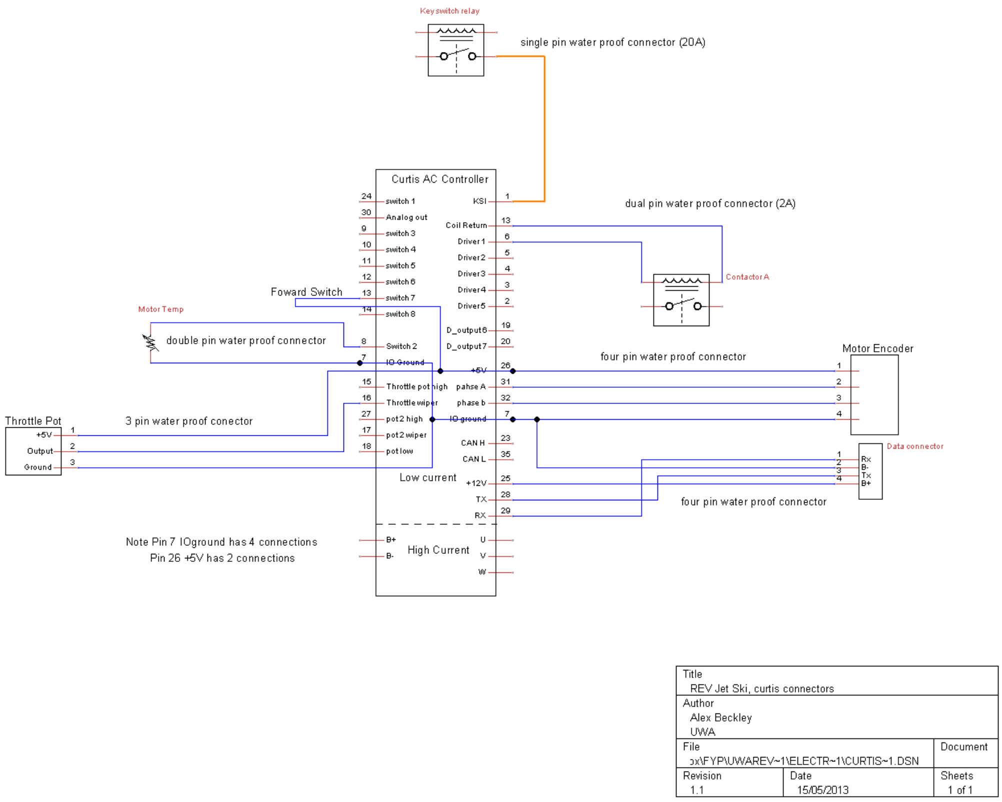
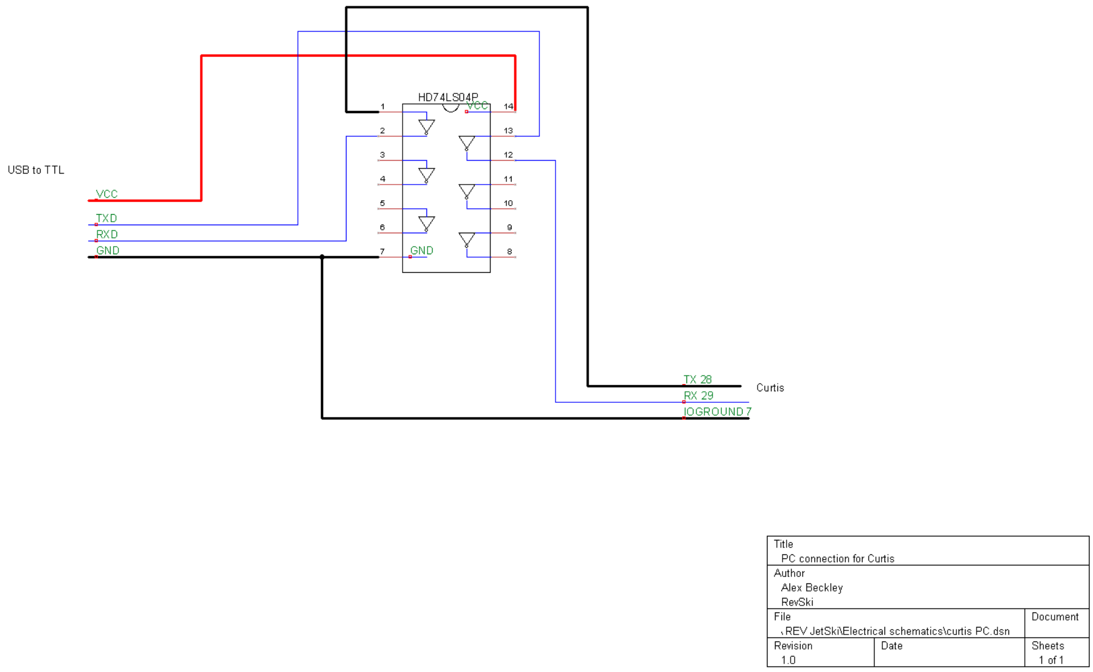


Figure 3: Curtis to PC Interface



Appendix C

Rev Jet Ski DC-DC converter Selection Overview

Requirements

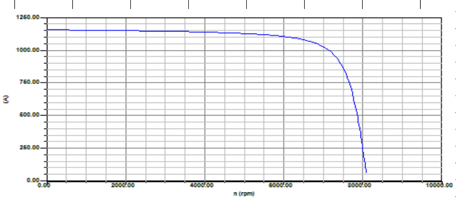
- 96V DC input
- 12V output (up to 14V)
- >10A output current
- We will not be hooking it up to a secondary 12V battery

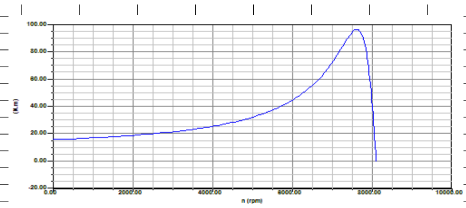
Options

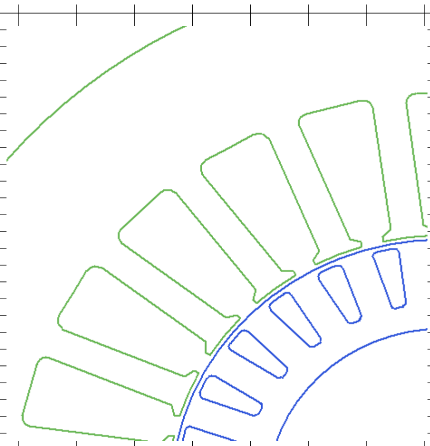
1. Ev power Australia
    - http://ev-power.com.au/webstore/index.php/dc-dc-converters/isolated-dc-dc-converters/dc-dc-converter-isolated-72-12vdc-30a-1.html
    - Satisfies all requirements
        i. Recommend to use a 12v battery
    - IP 64 Rated
    - 30A output
    - 174X1558X83 mm
    - $215Au + $25 shipping = total $240au
2. Kelly Controls
    - http://kellycontroller.com/hwz-series-dcdc-converter-96v-to-135v-25a-p-371.html
    - Satisfies all requirements
    - 25A out
    - Electronic key switch
    - 179X140X71mm
    - $149us + $50 postage = total $199us

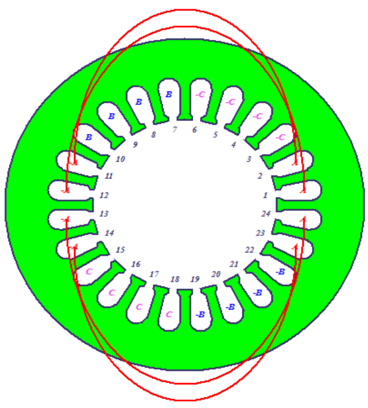
Appendix D: Motor Specifications

JS102-50kW 96V 135Hz 200mm				
16/09/2012				
				BEST
Given Output Power (kW):	50	50	50	50
Rated Voltage (V):	96	96	96	96
Winding Connection:	Delta	Wye	Wye	Wye
Number of Poles:	2	2	2	2
Given Speed (rpm):	8000	8000	8000	8000
Frequency (Hz):	135	135	135	135
Stray Loss (W):	250	250	250	250
Frictional Loss (W):	150	150	150	150
Windage Loss (W):	150	150	150	150
Type of Load:	Constant Power	tant Power	tant Power	tant Power
Operating Temperature (C):	75	75	75	75
STATOR DATA				
Number of Stator Slots:	24	24	24	24
Outer Diameter of Stator (mm):	224	224	224	224
Inner Diameter of Stator (mm):	110	110	110	110
Type of Stator Slot:	3	3	3	3
Dimension of Stator Slot				
hs0_stator (mm):	1	1	1	1
hs1_stator (mm):	1.12	1.12	1.12	1.12
hs2_stator (mm):	25.98	25.98	25.98	25.98
bs0_stator (mm):	4.5	4.5	4.5	4.5
bs1_stator (mm):	8.37091	8.37091	8.37091	8.37091
bs2_stator (mm):	15.2116	15.2116	15.2116	15.2116
rs_stator (mm):	2	2	2	2
Top Tooth Width (mm):	6.6	6.6	6.6	6.6
Bottom Tooth Width (mm):	6.6	6.6	6.6	6.6
Length of Stator Core (mm):	200	180	170	165
Stacking Factor of Stator Core:	0.95	0.95	0.95	0.95
Type of Steel:	DW315_50	DW315_50	DW315_50	DW315_50
Number of lamination sectors	1	1	1	1
Press board thickness (mm):	0	0	0	0
Magnetic press board	No	No	No	No
Number of Conductors per Slot:	7	4	4	4
Number of Parallel Branches:	2	2	2	2
Number of Wires per Conductor:	5	9	9	9
Type of Coils:	11	10	10	10
Coil Pitch:	11	11	11	11
Wire Diameter (mm):	2.4	2.4	2.4	2.4
Wire Wrap Thickness (mm):	0.08	0.08	0.08	0.08
Slot Insulation Thickness (mm):	0.23	0.23	0.23	0.23
Layer Insulation Thickness (mm):	0	0	0	0
Top Free Space in Slot (%):	0	0	0	0
Bottom Free Space in Slot (%):	0	0	0	0
Conductor Length Adjustment (mm):	0	0	0	0
End Length Correction Factor	1	1	1	1
End Leakage Reactance Correction Factor	1	1	1	1
Limited Slot Fill Factor (%):	75	75	75	75
ROTOR DATA				
Number of Rotor Slots:	28	28	28	28
Air Gap (mm):	1	1	1	1
Inner Diameter of Rotor (mm):	70	70	70	70
Type of Rotor Slot:	4	4	4	4
Dimension of Rotor Slot				
hr0_top (mm):	1	1	1	1
hr01_top (mm):	1	1	1	1
hr1_top (mm):	1	1	1	1
hr2_top (mm):	11	11	11	11
br0_top (mm):	0.0001	0.0001	0.0001	0.0001
br1_top (mm):	5.3	5.3	5.3	5.3
br2_top (mm):	2.93	2.93	2.93	2.93
rr_top (mm):	0.5	0.5	0.5	0.5
Cast Rotor:	No	No	No	No
Half Slot:	No	No	No	No
Length of Rotor (mm):	200	180	170	165
Stacking Factor of Rotor Core:	0.95	0.95	0.95	0.95
Type of Steel:	DW315_50	DW315_50	DW315_50	DW315_50
Skew Width:	0	0	0	0
End Length of Bar (mm):	0	0	0	0
Height of End Ring (mm):	12	12	12	12
Width of End Ring (mm):	23	23	23	23
Resistivity of Rotor Bar				
at 75 Centigrade (ohm.mm^2/m):	0.0217391	0.021739	0.021739	0.021739
Resistivity of Rotor Ring				
at 75 Centigrade (ohm.mm^2/m):	0.0217391	0.021739	0.021739	0.021739
Magnetic Shaft:	Yes	Yes	Yes	Yes
MATERIAL CONSUMPTION				
Armature Copper Density (kg/m^3):	8900	8900	8900	8900
Rotor Bar Material Density (kg/m^3):	8900	8900	8900	8900









	Phase	Turns	In Slot	Out Slot
Coil_1	A	4	1	12
Coil_2	A	4	2	11
Coil_3	-C	4	5	16
Coil_4	-C	4	6	15
Coil_5	B	4	9	20
Coil_6	B	4	10	19

Rotor Ring Material Density (kg/m^3):	8900	8900	8900	8900
Armature Core Steel Density (kg/m^3):	7600	7600	7600	7600
Rotor Core Steel Density (kg/m^3):	7600	7600	7600	7600
Armature Copper Weight (kg):	13.6946	13.4328	13.085	12.911
Rotor Bar Material Weight (kg):	2.56644	2.30979	2.18147	2.11731
Rotor Ring Material Weight (kg):	1.4508	1.4508	1.4508	1.4508
Armature Core Steel Weight (kg):	31.1656	28.049	26.4907	25.7116
Rotor Core Steel Weight (kg):	5.58917	5.03025	4.75079	4.61106
Total Net Weight (kg):	54.4666	50.2727	47.9588	46.8018
Armature Core Steel Consumption (kg):	60.6851	54.6166	51.5823	50.0652
Rotor Core Steel Consumption (kg):	13.7228	12.3505	11.6644	11.3213
RATED-LOAD OPERATION				
Stator Resistance (ohm):	0.00543842	0.001646	0.001604	0.001582
Stator Leakage Reactance (ohm):	0.0697862	0.030588	0.029314	0.028663
Rotor Resistance (ohm):	0.00973848	0.002945	0.002828	0.002769
Rotor Leakage Reactance (ohm):	0.114821	0.03361	0.03196	0.031095
Resistance Corresponding to				
Iron-Core Loss (ohm):	66.605	19.5658	18.472	17.9222
Magnetizing Reactance (ohm):	3.20249	0.933966	0.874659	0.841934
Stator Phase Current (A):	211.085	374.624	370.868	369.366
Current Corresponding to				
Iron-Core Loss (A):	1.32784	2.53589	2.70646	2.79891
Magnetizing Current (A):	27.6162	53.1247	57.1579	59.5801
Rotor Phase Current (A):	200.952	355.876	351.28	349.223
Copper Loss of Stator Winding (W):	726.957	693.201	661.777	647.703
Copper Loss of Rotor Winding (W):	1179.77	1119.02	1046.85	1013.15
Iron-Core Loss (W):	352.305	377.467	405.919	421.202
Frictional and Windage Loss (W):	293.627	294.318	295.142	295.529
Stray Loss (W):	250	250	250	250
Total Loss (W):	2802.66	2734	2659.69	2627.59
Input Power (kW):	52.7998	52.7307	52.6574	52.6265
Output Power (kW):	49.9971	49.9967	49.9977	49.9989
Mechanical Shaft Torque (N.m):	60.3256	60.2539	60.1705	60.1324
Efficiency (%):	94.6919	94.8152	94.9491	95.0071
Power Factor:	0.864412	0.842504	0.849849	0.8528
Rated Slip:	0.0229212	0.021767	0.020391	0.019747
Rated Shaft Speed (rpm):	7914.34	7923.69	7934.84	7940.05
NO-LOAD OPERATION				
No-Load Stator Resistance (ohm):	0.00543842	0.001646	0.001604	0.001582
No-Load Stator Leakage Reactance (ohm):	0.0699069	0.030638	0.02936	0.028706
No-Load Rotor Resistance (ohm):	0.00973671	0.002945	0.002827	0.002769
No-Load Rotor Leakage Reactance (ohm):	1.54912	0.422163	0.371975	0.351156
No-Load Stator Phase Current (A):	29.4628	57.6597	61.5321	63.8776
No-Load Iron-Core Loss (W):	397.431	441.446	466.888	480.721
No-Load Input Power (W):	980.969	1003.95	1069.09	1080.06
No-Load Power Factor:	0.0861456	0.078639	0.080057	0.07815
No-Load Slip:	0.000117516	0.000101	0.00011	0.000106
No-Load Shaft Speed (rpm):	8099.05	8099.18	8099.11	8099.14
BREAK-DOWN OPERATION				
Break-Down Slip:	0.07	0.06	0.06	0.06
Break-Down Torque (N.m):	97.6001	88.0791	93.3874	96.258
Break-Down Torque Ratio:	1.61789	1.4618	1.55205	1.60077
Break-Down Phase Current (A):	459.015	735.892	773.1	793.152
LOCKED-ROTOR OPERATION				
Locked-Rotor Torque (N.m):	20.1279	13.9218	15.0851	15.887
Locked-Rotor Phase Current (A):	688.392	1048.63	1115.01	1156.73
Locked-Rotor Torque Ratio:	0.333655	0.231053	0.250706	0.264201
Locked-Rotor Current Ratio:	3.26121	2.79915	3.00649	3.13165
Locked-Rotor Stator Resistance (ohm):	0.00543842	0.001646	0.001604	0.001582
Locked-Rotor Stator				
Leakage Reactance (ohm):	0.0681067	0.030271	0.028918	0.028178
Locked-Rotor Rotor Resistance (ohm):	0.0126702	0.003807	0.003642	0.003559
Locked-Rotor Rotor				
Leakage Reactance (ohm):	0.0717822	0.022858	0.021015	0.019931
DETAILED DATA AT RATED OPERATION				
Stator Slot Leakage Reactance (ohm):	0.0304867	0.017918	0.016923	0.016426
Stator End-Winding Leakage				
Reactance (ohm):	0.0242114	0.00827	0.00827	0.00827
Stator Differential Leakage				
Reactance (ohm):	0.0150879	0.0044	0.004121	0.003967
Rotor Slot Leakage Reactance (ohm):	0.0964679	0.028137	0.026765	0.02606
Rotor End-Winding Leakage				

Reactance (ohm):	0.00370488	0.00121	0.00121	0.00121
Rotor Differential Leakage				
Reactance (ohm):	0.0146088	0.00426	0.00399	0.003841
Skewing Leakage Reactance (ohm):	0	0	0	0
Net Slot Area (mm^2):	315.218	315.218	315.218	315.218
Slot Fill Factor (%):	68.2906	70.2418	70.2418	70.2418
Stator Winding Factor:	0.957662	0.957662	0.957662	0.957662
Stator-Teeth Flux Density (Tesla):	1.14383	1.25414	1.32734	1.37348
Rotor-Teeth Flux Density (Tesla):	1.02331	1.122	1.18748	1.22876
Stator-Yoke Flux Density (Tesla):	1.04835	1.15148	1.22073	1.26535
Rotor-Yoke Flux Density (Tesla):	0.710646	0.780549	0.827493	0.857741
Air-Gap Flux Density (Tesla):	0.498079	0.546113	0.577986	0.598078
Stator-Teeth Ampere Turns (A.T):	4.4496	6.6522	9.64217	12.4226
Rotor-Teeth Ampere Turns (A.T):	1.44999	1.8394	2.2556	2.64017
Stator-Yoke Ampere Turns (A.T):	13.3593	17.6987	21.368	24.7974
Rotor-Yoke Ampere Turns (A.T):	1.2412	1.30733	1.34354	1.37442
Air-Gap Ampere Turns (A.T):	486.453	533.366	564.495	584.118
Correction Factor for Magnetic				
Circuit Length of Stator Yoke:	0.7	0.7	0.65825	0.631193
Correction Factor for Magnetic				
Circuit Length of Rotor Yoke:	0.562677	0.533892	0.514561	0.502105
Saturation Factor for Teeth:	1.01213	1.01592	1.02108	1.02579
Saturation Factor for Teeth & Yoke:	1.04214	1.05155	1.06131	1.07059
Induced-Voltage Factor:	0.921266	0.895197	0.901993	0.905029
Stator Current Density (A/mm^2):	4.666	4.60056	4.55443	4.53599
Specific Electric Loading (A/mm):	51.3091	52.0349	51.5131	51.3046
Stator Thermal Load (A^2/mm^3):	239.408	239.39	234.613	232.717
Rotor Bar Current Density (A/mm^2):	12.3835	12.5314	12.3694	12.2966
Rotor Ring Current Density (A/mm^2):	9.34159	9.4532	9.33094	9.27604
Half-Turn Length of				
Stator Winding (mm):	404.918	386.146	376.146	371.146
WINDING ARRANGEMENT				
The 3-phase, 1-layer winding can be arranged in 24 slots as belov		10	10	10
AAAAZZZZBBBBXXXXCCCCYYYY		15	15	15
		82.5	82.5	82.5
Average coil pitch is:	10	0	0	0
Angle per slot (elec. degrees):	15			
Phase-A axis (elec. degrees):	112.5			
First slot center (elec. degrees):	0			
		16	16	16
TRANSIENT FEA INPUT DATA		2	2	2
		0.001646	0.001604	0.001582
For one phase of the Stator Winding:		9.75E-06	9.75E-06	9.75E-06
Number of Turns:	28			
Parallel Branches:	2	8.31E-07	8.31E-07	8.31E-07
Terminal Resistance (ohm):	0.00543842	1.42E-09	1.42E-09	1.42E-09
End Leakage Inductance (H):	2.85E-05			
For Rotor End Ring Between Two Bars of One Side:		180	170	165
Equivalent Ring Resistance (ohm):	8.31E-07	0.95	0.95	0.95
Equivalent Ring Inductance (H):	1.42E-09	0.95	0.95	0.95
2D Equivalent Value:		0.018753	0.017711	0.01719
Equivalent Model Depth (mm):	200			
Equivalent Stator Stacking Factor:	0.95			
Equivalent Rotor Stacking Factor:	0.95			
Estimated Rotor Inertial Moment (kg m^2):	0.0208362			

Appendix E: Encoder Specification Sheet

LARM

Magnetic incremental encoders MIRC300, 305, 310, 315, 320 and 325

MIRC30x – synchro flange, external diameter of the shaft 6 mm
MIRC31x – clamping flange, external diameter of the shaft 10 mm
MIRC32x – stator coupling, blind hollow shaft internal diameter 12 mm

The magnetic incremental rotary encoders type MIRC300, 305, 310, 315, 320 and 325 working on magnetic Hall Effect principle. The encoder converts rotary motion to electrical incremental signals. Electrical signals provide information of bilateral position of two mechanical parts, angle turn or rotary motion. A typical use is in conjunction with digital control system or drivers for control of the electric motors.

Type identification

MIRC3 x x / xxxx xx x

OPTION (example)
P – Pinion sticked to the shaft

OUTLET
PA – Cable 1 m axial
PB – Cable 1 m radial
KA – Connector type CONTACT axial
KB – Connector type CONTACT radial
(longer cable on request)

NUMBER OF IMPULSES (PERIODS) PER ROTATION
from 1 to 128 after one pulse, further 200, 250, 256, 400, 500, 512, 1024, 2048 with one zero impulse per rotation.

OUTLETS IDENTIFICATION

	Supply voltage	Outlet
0	– +10 ÷ +30 V	HTL line driver
5	– + 5 V	line driver

DIAMETER OF SHAFTS
0 – external dia. of the shaft 6 mm
1 – external dia. of the shaft 10 mm
2 – internal dia. of the shaft 12 mm
(other diameter on request)

TYPE OF ENCODER
3 – magnetic incremental encoder type MIRC3xx

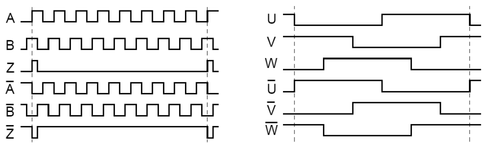
Technical data

ELECTRICAL DATE / TYPE	MIRC300, 310, 320	MIRC305, 315, 325
Impulses (periods) per rotation	1 to 2048	
Resolution (positions per revolution) = impulses x 4	Up to 8192	
Supply voltage max. U_N (V)	from +10 to +30	+ 5 ± 5%
Supply current max. I_N (mA)	60@30V	50
Output frequency max. F_O (kHz)	200	
Output max. I_O (mA)	± 25	± 20
Output	HTL line driver	line driver (RS 422)

Mechanical data and working conditions

Rotational speed max.	10000 min.$^{-1}$
Angular acceleration max.	40000 rad.s^{-2}
Moment of inertia of mechanical parts max.	10 g.cm^2 ± 10 %
Vibration according to FCČSN345791	10g_n (10 to 2000 Hz)
Shock max.	50g_n (100 ms)
Shaft loads MIRC300, 305 / / MIRC 310, 315, 320, 325 – axial max.	20/40 N
– radial max.	50/60 N
Working temperature	– 25° to + 80° C
Humidity relative / absolute	max. 95 % / max. 40g.m^{-3}
Atmosphere (without aggressive substances)	73,3 to 126,6 kPa
Type of protection	IP65
Weight MIRC300, 305 / MIRC310, 315, 320, 325	ca. 0,25 / 0,35 kg
Length cable max.	50 m

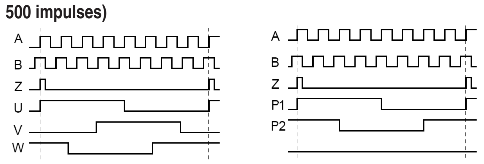
Output signals
MIRC300, 305 / MIRC310, 315 / MIRC320, 325



ABZ differential incremental signals UVW differential commutation signals

Number of incremental impulses (periods) per rotation: from 1 to 128 after one pulse, further 200, 250, 256, 400, 500, 512, 1024, 2048 with one zero impulse per rotation.
Resolution in positions = Number impulses per rotation (lines) x 4.

MIRC305 / MIRC315 / MIRC325
only and into resolution 1024 impulses (without 200, 250, 400 and 500 impulses)



ABZ incremental / UVW commutation ABZ incremental signals / period counter

Assembly
The MIRC30x encoder is installed into appropriate equipment using 3xM4 screws or a groove. The position of the shaft is explicitly determined by a fitted diameter of 50h7. The MIRC31x encoders are installed using 3xM3

continued on next page

LARM a.s., Triumf 413, 384 11 Netolice, ČR Tel.:+420 388 386 211, Fax:+420 388 386 212, e-mail: sales@larm.cz

Description of connection elements MIRC300, 305, 310, 315, 320 and 325

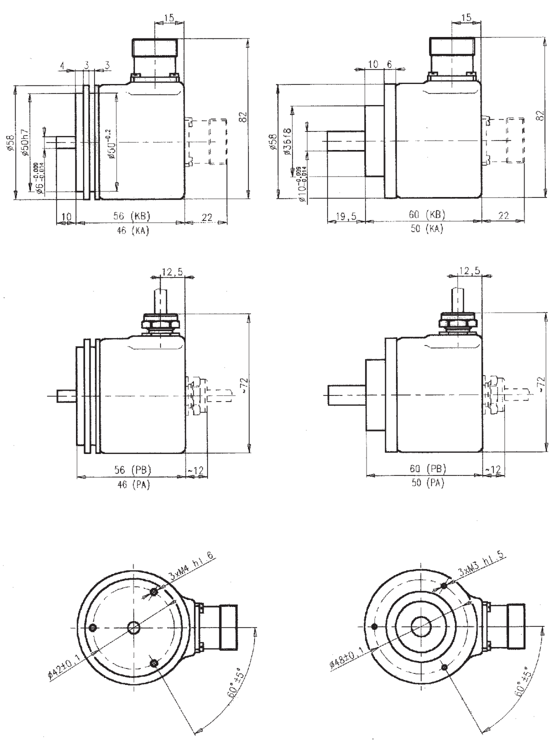
Pin connector type CONTACT	Colors of connection cable	Significance			
		Incremental	Commutation	Incr./commu.t.	Incr./counter
1	Grey	B non	V non	V	P2
2	Pink	Sensor + 10 to + 30 V for **MIRC300, 310 and 320** Sensor + 5 for **MIRC305, 315 and 325**			
3	Blue	Z	W	Z	Z
4	Violet	Z non	W non	W	NC
5	Yellow	A	U	A	A
6	White	A non	U non	U	P1
7	–	NC			
8	Green	B	V	B	B
9	Shield	Shield			
10	Black	GND			
11	Brown	Sensor 0 V			
12	Red	U_N + 10 V to + 30 V for **MIRC300, 310 and 320** V_{cc} + 5 V for **MIRC305, 315 and 325**			

Assembly – continued from previous page

screws and the position of the shaft is explicitly determined by a diameter of 36f8. It is recommended to use appropriate homokinetic coupling (see the catalogue sheet „Accessories"). The encoder MIRC320 or MIRC325 with stationary coupling is installed on the shaft of appropriate equipment and tightened by two imbus screws M4. Afterwards the encoder is turned to the required position and the stationary coupling is fixed by two or four (optimal) screws M3. The connection has to be designed so as to avoid exceeding the maximum admissible radial or axial load applied to the shaft and it is necessary to keep the connection aligned. The cable of the MIRC3xx encoder must be fastened so as to avoid stress on the encoder by is own weight. In wet environments with running or splashing water it is recommended not to position the MIRC3xx encoders with the shaft pointing upwards.
When temperature is less then –5°C cable must be fixed.

Dimensioned drawing

MIRC300, 305 MIRC310, 315



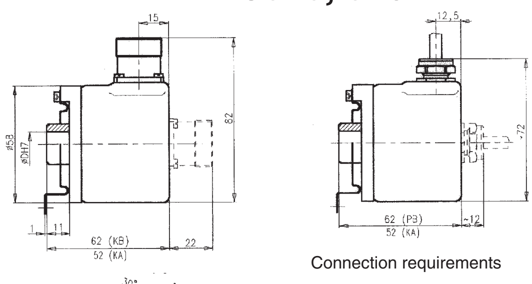
How to order?

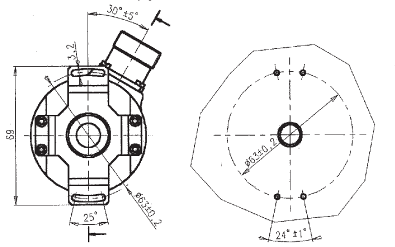
Please indicate encoder type, number of impulses per rotation, outlet, number of pieces, delivery term and other non-standard features. Connecting cable and homokinetic diaphragm couplings can be ordered as well [see Accessories catalogue list].

Example

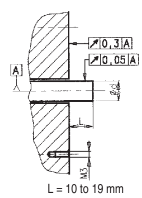
20 pcs MIRC300/1024KB and 20 pcs coupling SV9 and 20 pcs encoder holder. Delivery term – two weeks.

MIRC320, 325





Connection requirements



L = 10 to 19 mm
option Ø dg7

Appendix F: Instructions for Connecting the Curtis 1238 to a Computer

Alex Beckley 20143494
RevSki

Instructions for wiring connect Curtis 1238 to computer

You will need the following components:

- USB to TTL converter (http://cgi.ebay.com.au/ws/eBayISAPI.dll?ViewItem&item=200805058916&ssPageName=ADME:L:OC:AU:3160)
- Hex inverter (HD74LS04)
- Small gauge wires to connect everything up
- Curtis software
- Windows XP laptop. (not windows 7)

Steps

1. Wire up the components according to the figure 1
2. Install drivers for USB to TTL converter
3. Install Curtis software
4. Connect the USB to TTL converter
5. Run Curtis software
6. From the options menu go to ' Change Protocol/Port'
7. Choose enhanced serial and the correct com port
8. It should now connect ☺

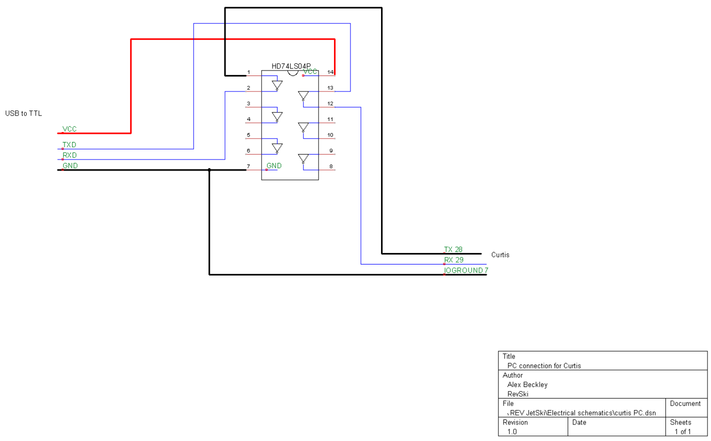


Figure 1

Appendix G: Curtis AC Motor Characterization Procedure

1234/36/38 and 1298 Automated AC Motor Characterization Procedure for OS12

⚡ WARNING - MOTOR WILL ROTATE DURING THIS TEST ⚡

This test procedure is performed in two stages, and is different for traction and hydraulic systems. Both stages must be completed for proper controller setup.

STAGE 1 (Traction or Hydraulic)

If characterizing a traction system, the vehicle should have its drive wheels clearly off ground, and the vehicle should be safely blocked from accidental movement. The drive wheels should be freely spinning – any dragging brake or excessive friction may invalidate this test, or cause it to fail.

If characterizing a hydraulic system, the motor should be unbolted from the hydraulic pump and allowed to spin freely. The test will not work properly if the motor is left connected to the pump.

These tests need to be run again if the maximum controller current is increased more than 20%, or if the winding configuration is changed (Delta to Wye(Star) or vice versa).

1. Setup Throttle (and Brake, if applicable).
2. Setup Nominal Battery Voltage.
3. Setup main contactor driver pull-in and holding percentages.
4. If an EM Brake is present and wired into the controller, set EM Brake Enable to ON, and setup EM Brake driver pull-in and holding percentages. If the EM Brake is controlled external, it must be released for this test procedure.
5. Setup Interlock Type.
6. Setup motor temperature sensor (Program/Motor/Temperature Control) and verify proper operation (Monitor/Motor/Motor Temperature). If no temperature sensor is present, set Sensor Enable to OFF. Operation with a temperature sensor is highly recommended, both for protection and motor control efficiency. If no motor temperature sensor is present, the characterization routines assume that the motor is approximately room temperature (30 deg C). Do not characterize a warm motor without a temperature sensor.
7. Enter the number of motor poles in the Motor Control Tuning/Motor Characterization Tests/Motor Poles parameter. The vast majority of induction motors will have 4 poles.
8. Enter the maximum desired speed for the characterization test in the Motor Control Tuning/Motor Characterization Tests/Max Test Speed. Note this speed might not be achieved, depending on system characteristics – this is normal. 1000 RPM is a typical setting.
9. Enter the maximum desired current for the characterization test in the Motor Control Tuning/ Motor Characterization Tests/Max Test Current. 80% is a typical setting (Note this is 80% of the maximum controller rating). Generally this is only reduced if motor heating during the test is a problem, or resonance in the motor occurs at high currents.
10. Using the 1311, clear Fault History. (Faults/Clear Fault History)
11. Ensure that Interlock is enabled (1311 Monitor/Inputs/Interlock)
12. Set Program/Motor Control Tuning/Motor Characterization Tests/Test Enable to 1
13. Check if any faults are present.

⚡ WARNING – Motor will start to rotate after next step ⚡

14. Set Motor Control Tuning/Motor Characterization Tests/Test Throttle to +1.
15. After a moment, the motor will begin to rotate. It is **CRITICAL** that you verify that the motor is turning in the **FORWARD** vehicle direction. If not, set Test Throttle to 0, wait for the motor to come to a stop, then set Test Throttle to –1.

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16. This Motor Characterization test may take several minutes. When the automated test is complete, the controller will have a Parameter Change Fault. This is normal. Check if other faults are present. A Characterization Error fault can be determined by reading the number at Monitor/Controller/Motor Characterization Error and referencing the following table:

Motor Characterization Error
0 -- Sequencing error. Normally caused by turning off Motor_Characterization_Test_Enable before running test. Needs controller reset.
1 -- Encoder size identification failure (but encoder pulses are valid, this will set Encoder Steps to 31, and require that you set it manually. Only encoder sizes of 32, 48, 64, and 80 will be automatically identified.)
2 -- Motor Temperature Sensor fault
3 -- Motor_Temperature > 150 deg C (only active when temp sensor is present)
4 -- Controller Overtemperature
6 -- Battery Undervoltage
7 -- Battery Severe Overvoltage
8 -- Encoder Characterization Error (one or both channels missing)
9 -- Motor parameter out of characterization range (check to be sure motor has no load)

NOTE: An Encoder_Char_Error will also be indicated if an Encoder size identification error occurs (Motor Characteriziation Error = 1)

17. KSI power should now be cycled.

The motor control should now be operational, though likely poorly optimized – The SlipGain test is VERY IMPORTANT for most, but not all, motors – you won't know which until you perform the test and get the result. The following steps will complete the optimization process. Note that no cutbacks should be in effect (thermal, voltage, etc) when these tests are run.

Appendix H:

Rev Jet Ski Battery charger Selection Overview

Battery Charger requirements:

- LiFePO4 compatible
- 240V 50hz AC input
- 96V output
- Self protection (over voltage, reverse connection, short circuit)
- Battery protection (over voltage, under voltage)
- Connects too BMS for auto cut-off. (allows for plug in and leave charging)
- Maximum charging current of 160A

Options

1. GWL/power charger from ev-power.eu
    - http://www.ev-power.eu/Chargers-48V-to-96V/Charger-96V-25A-for-LiFePO4-LiFeYPO4-BMS-option.html
    - 25A charging current
    - Satisfies all requirements
    - $572us + $204 shipping = $776us
2. GWL/power charger from ev-power.eu (smaller)
    - http://www.ev-power.eu/Chargers-TC-1-5-kW/Charger-for-LiFe-Y-PO4-96V-12A-1-5-kW-TCCH-H116-8-12.html
    - 12A charging current
    - Satisfies all requirements
    - $319us + $204 shipping = $523us
3. Kingpan from ev-works
    - http://www.evworks.com.au/index.php?product=CHG-KP09615KL
    - Local supplier
    - 15A charging current
    - Does not feature BMS connection
    - Not sure about battery protection, kingpan website is incomplete
    - $695AU does not require shipping.

Notes:

Charging time:

Our battery pack is 96V and 80Ah.
Thus for charging from 50% to full the chargers would take approx: (for the above chargers

1. 1.6 Hours
2. 3.3 Hours
3. 2.6 Hours

Appendix I: MSDS

	Lithium Iron Phosphate Chemistry	Date: 7/27/10	
MATERIAL SAFETY DATA SHEET (MSDS)		Rev.	1.3

Section 1. Product And Company Identification

Product name: Li-Ion Cells or Battery Pack
Product description: Lithium Iron Phosphate Chemistry
Product Size: Large Format Prismatic Type Cell (for all sizes)
Company Name: International Battery, Inc.
Address: 6845 Snowdrift Road, Allentown, PA-18106, USA
Telephone Number: 610-366-3925
Fax Number: 610-366-3929
Emergency Telephone Number: Chemtrec for Spills, Leaks,
USA 1-800-424-9300
International 703-527-3887

Section 2. Composition/Information on Ingredients

Common Chemical Name	CAS #	Percent of Content (%)	Classification and Hazard Labelling
Lithium Iron Phosphate ($LiFePO_4$)	15365-14-7	30-33	Eye, Skin, Respiratory Irritant
Carbon, as Graphite	7440-44-0	15-17	Eye, Skin, Respiratory Irritant
Aluminum metal	7429-90-5	5-7	Inert
Copper metal	7440-50-8	7-9	Inert
Electrolyte		15-20	Mixture: Flammable; Reactive; Sensitizer; Eye, Skin & Respiratory Irritant
Ethylene carbonate	96-49-1		
Dimethyl carbonate	616-38-6		
Ethyl methyl carbonate	623-53-0		
Lithium Hexafluorophosphate	21324-40-3		

Section 3. Hazardous Identification

Lithium Ion batteries described in this MSDS data sheet are hermetically sealed and designed to withstand temperatures and pressures encountered during normal use. Under normal conditions of use, there is no physical danger of ignition, explosion or chemical danger of hazardous materials leakage. The materials contained in this battery may only represent a hazard if the integrity of the battery is compromised or if the battery is mechanically, thermally or electrically abused.

Caution: Do not open or disassemble the batteries. Do not expose the batteries to fire or open flame. Do not mix batteries of varying sizes, chemistries, or types. Do not short circuit, puncture, incinerate, crush, over-charge, over discharge, or expose the batteries to temperatures above the declared limit. Abuse of the batteries will result in the risk of fire or explosion, which could release hydrogen fluoride gas.

Human Health Hazard: Electrolyte may irritate skin and eyes. In the event of a battery rupture, electrolyte fumes/gases can cause serious damage to the eye and can cause sensitization and irritation to the respiratory tract.

Section 4. First Aid Measures

General: In an event of battery fire or rupture, evacuate personnel from the contaminated area.
Eye contact: Flush with plenty of water for at least 15 minutes (eyelids held open). Seek medical attention immediately.
Inhalation: Leave area immediately. Seek medical attention immediately.
Skin contact: Remove contaminated clothing. Wash the area with soap and plenty of water immediately and for at least 15 minutes. Seek medical attention.
Ingestion: Drink plenty of water and induce vomiting. Seek medical attention immediately.

Section 5. Fire Fighting Measures:

Extinguishing Media: Plenty of water, Carbon dioxide gas, Chemical powder, fire extinguishing medium and foam.
Fire Fighting Procedures: Use a positive pressure self-contained breathing apparatus if batteries are involved in fire. Full protective clothing is necessary. During water application, caution is advised as burning pieces of flammable particles may be ejected from the fire.
Hazardous Combustion products: Fire, excessive heat and/or over voltage conditions may produce hazardous decomposition products (i.e. electrolyte fumes and hazardous organic vapors). Vapors may be heavier than air and may travel along the ground or be moved by ventilation to an ignition source.

Section 6. Accidental Release Measures:

Remove all personnel from the area immediately. Wear protective gloves and protective glasses. The spilled solids are to be put into a sealed plastic bag or container and disposed off properly (after cooling if necessary). Any leaked electrolyte should be wiped off with dry cloth and disposed off properly (section 13). Do not inhale the gas and avoid skin contact. Do not bring collected materials close to fire.

Section 7. Handling and Storage:

Handling: Do not open or disassemble the batteries. Do not expose the batteries to fire or store near open flame. Do not mix batteries of varying sizes or chemistries. Do not connect the positive and negative battery terminals with conductive material or throw into fire. Do not heat or solder the batteries. Keep the batteries in plastic or non-conductive trays. Do not expose batteries to direct sun light for a prolonged time.

Storage: Batteries should be stored in a well ventilated, cool area with sufficient clearance between batteries and walls. Store the batteries in a cool (below 30^0C) area and away from moisture. Keep the batteries away from sources of heat, open flames, food and drink. Do not store the batteries above 55^{0}C or below -30^{0}C . Storing at elevated temperatures may reduce the life of batteries. Keep batteries away from strong oxidizers and acids. Elevated temperature storage such as 100^{0}C may result in battery venting flammable liquid and gases.

Section 8. Exposure Controls/Personal Protection:

No engineering controls are required for normal operation. In case of cell leakage, increase the ventilation and use self contained full-face respiratory equipment.

Common Chemical Name/General Name	OSHA PEL-TWA	ACGIH (2010) TLV-TWA
Lithium Iron Phosphate	10.0 mg/m^3 (as iron fume)	5.0 mg/m^3 (as iron fume)
Carbon, As Graphite	5.0 mg/m^3 (respirable fraction)	2.0 mg/m^3 (respirable fraction)
Electrolyte	Not Established	Not Established

OSHA: Occupational Safety and Health Administration
PEL-TWA: Permissible Exposure Limits-Time Weighted Average Concentration
ACGIH: American Council of Government Industrial Hygienists
TLV-TWA: Threshold Limit Value-Time Weighted Average Concentration

Personal Protective Equipment

Not required during normal use of the battery
In the event of a ruptured battery or fire

Respiratory Protection: Self-contained full-face respiratory equipment.
Hand Protection: Chemical protective gloves.
Eye protection: Self-contained full-face respiratory equipment.
Skin and body protection: Chemical-protective clothing.

Section 9. Physical and Chemical Properties:

Appearance: Green/Blue plastic cases with or without ribs hermetically sealed and fitted with metallic terminals/connections.
Odor: No odor
pH: NA
Flash Point: NA
Explosion properties: NA
Density: NA
Solubility with indication of Solvent(s): Insoluble in water.

Section 10. Stability and Reactivity:

Stability: Stable under normal conditions.
Reactivity: When a battery is exposed to high temperatures, crushes, deformation, and external short circuit may result in venting harmful gases and volatile organics. In the event of rupture, hydrogen fluoride gas is produced in reaction with water.

Section 11. Toxicological Information:

There is no available data for the product itself. The information for the internal cell materials are as follows:
Irritancy: The electrolytes contained in the battery can irritate eyes with any contact. Prolonged contact with skin or mucus membrane may cause irritation.
Sensitization: The nervous system of respiratory organs may be stimulated sensitively.
Carcinogenicity: No information is available at this time.
Reproductive toxicity: No information is available at this time.
Teratogenicity: No information is available at this time.
Mutagenicity: No information is available at this time.

Section 12. Ecological Information:

Not applicable for this product.

Section 13. Disposal Considerations:

Batteries should be discharged fully prior to disposal. The battery terminals should be capped to prevent a short circuit. Dispose the batteries in accordance with applicable local laws. Li-ion batteries may be subject to federal, state or local regulations.

Section 14. Transportation information:

In the case of transportation, avoid exposure to high temperature and prevent the formation of any condensation. The container must be handled carefully. Prevent the collapse of the cargo piles and wetting by rain. Please refer to section 7 for handling and storage instruction.
UN classification: International Battery, Inc. products' shipping name is "Lithium ion batteries".

Section 15. Regulatory information:

The transport of rechargeable lithium-ion batteries is regulated by various bodies (IATA, IMO, ADR, US-DOT) that follow the United Nations "Recommendation on the Transport of Dangerous Goods, Model regulations, 13th Revised edition-2003-Ref. STSG/AC.10/1 Rev. 13".
International Battery, Inc. products are assigned to UN3480 and are restricted by this regulation.

Section 16. Other Information/Disclaimer:

The information contained in this material data sheet has been compiled from sources considered to be dependable and is to the best of the knowledge and belief of International Battery, Inc., accurate and reliable as of the date of compilation. However, no representation, warranty (either expressed or implied) or guarantee is made to the accuracy, reliability or completeness of the information obtained herein. This information relates to the specific materials designated and may not be valid for such materials used in combination with any other materials or in any process. It is the user's responsibility to satisfy himself as to the suitability and completeness of this information for his particular use.

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