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# Motor Comparison & Selection For Electric Jet Ski

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## **Abstract**

Jet skis, traditionally powered by diesel or petrol engines, have good performance but at the expense of emitting pollutants and producing noise. The REV Project aims to convert a traditional petrol-powered Jet ski to full electricity-powered one, eradicating pollution to environment while maintaining good performance.

Motor, regardless of type, is one of the most important components of any electric vehicle. It is responsible for delivering mechanical energy by using electric energy as power source. For this Jet ski project, the motor powered by batteries is designed to drive the impeller connected to it. With many choices of motors available on the market, asynchronous motor, synchronous motor and two types of DC motors have been selected for investigation from a theoretical point of view in conjunction with real context, i.e, the electric Jet ski. Meanwhile, commercially available motors of each type are selected in order for further practical comparison by taking into account several practical factors. Though limited in motor types and specific models, the investigation and comparison together are expected to provide both justification for the Jetski motor selection and reference work for future similar projects.

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# 1 Introduction

## 1.1 Project Background

Jetskis are widely seen in Australia today as a leisure activity. However, the popularity of Jetskis comes with negative impact on the environment owing to the use of petrol or diesel engines(Pearce, 1998). They produce pollutants to the environment and noise. According to a research by the International Maritime Organization(IMO) on air pollution from ships, nitrogen emissions worldwide from ship are equivalent to about 40% of nitrogen emissions in the North America, while sulfur emissions from ship are equal to about 35% of sulfur emissions in North America. 14% of total nitrogen emissions from fossil fuels are contributed by ship, compared to 16% of sulfur<sup>[1]</sup>. All these figures have an implication that ship emissions now are equally serious to car emissions that call efforts to seek alternatives to fossil fuel-powered vehicles. In contrast, electric vehicle, not just confined to electric cars, is well known for its local zero emissions and low global emissions, though they have not replaced conventional fossil fuel-powered vehicles due to high cost(Chan and Chau, 2001).

In an attempt to eliminate and eradicate the pollution problems of conventional Jetskis, the UWA Renewable Energy Vehicle (REV) Project launched a project in 2012 with sponsorship, aiming to convert a traditionally petrol-powered Jetski to a full electricity-powered one. The base vehicle, shown in Figure 1, was a 2008 Seadoo 4-TEC purchased with engine and fuel tank removed which seats 1 or 2 passengers.



Figure 1 Base Jetski<sup>[2]</sup>

## 1.2 Project Overview

The project has been going on since 2012 strictly under both Australian and university's safety rules to ensure safe production. The project was launched with four phases, i.e. design, construction, testing and evaluation. The project began with designs of all components required for an electric vehicle, with focus on drive train system including battery, motor, controller, etc. Designs involved both selection of required components which were commercially available and layout of them given the purchased Jetski. This took students involved in this stage about one year to complete design and selection of components required from scratch.

Upon completion of the design stage, the project proceeded to the construction stage which involved installation of all components selected as well as adjustment of designs when necessary changes are required. The work that first had been done in this stage was mounting all components, i.e, battery packs, motor, motor controller, safety system, bilge pump, etc, while the following work done included establishing electrical connections in accordance with designs and adjusting them when required.

The third stage that is underway focuses on performing lab test and on-water test of the converted Jetski in order to obtain test results and data to verify those initial designs. By the end of the second semester of 2015, lab test was successfully performed with the attention on running the motor with the Jetski located on the trailer. On-water test that is still underway includes three phases, i.e, floating test, powered-on test with limited throttle and powered-on test with varied throttle. Floating test which was already completed verified initial designs by proving that the converted Jetski is able to float safely on water with changes made inside the boat and still able to carry two passengers as it was. The powered-on test with limited throttle was also successfully performed, which demonstrated the manoeuvrability of the Jetski and paved the way for the ongoing powered-on test with varied throttle aiming to show the overall performance of this electric Jetski and to obtain as much data as possible for future analysis and improvement. Video of one of the powered-on water tests performed is available at <https://www.youtube.com/watch?v=6rNpSZly3C8>. Some photos of on-water tests are available in Appendix A.

It is expected that by the end of 2015 or from 2016 the last stage of this project will be launched, with focus on evaluation where conclusions regarding this converted Jetski will be made covering all information concerned, e.g, test results and analysis. However, future work may also include continuous improvement of the Jetski performance, e.g. prolonging the drive time from 30 minutes recorded from on-water tests performed in the current stage by using battery cells of larger capacity and establishing DC recharging system which will significantly shorten the charging time.

# 2 Motor Comparison

## 2.1 Motor Introduction

Motor, regardless of types and brands, is crucial to the operation of the Jetski. It therefore necessitated the writer's attention in this project. When considered individually, most commercially used motors are capable of delivering desired performance enabling the Jetski to move. However, when taking compatibility or suitability into account, efforts become more rewarding of figuring out the most suitable motor from available options for a given context. It is both technically and economically important to select a motor of the most suitable type and model for the Jetski. The first reason is with the motor to be selected, the converted Jetski is highly expected to be as competitive in manoeuvrability largely determined by the motor used as the petrol-powered one. The second reason is the limited budget that constrains motor selection. Therefore, a balance between high performance of available motors and cost needs to be maintained.

In this thesis, details of four commonly used motors, i.e. synchronous, asynchronous, brushed DC and brushless DC motors are first selected for discussion mainly from a theoretical point of view given the Jetski context, while some specific commercially available motors typical of these four categories of motors are compared in the second part by taking some important factors into account in order to provide both justification for Jetski motor selection and reference work for future similar projects.

## 2.2 Motor Literature Review

Electric motors can convert energy gained from electricity to mechanical energy in order to propel vehicles<sup>[3]</sup>. Electric motors can be classified by different ways. For instance, self-commutated and externally-commutated motors, classified by type of motor commutation. They can also be distinguished by the source by which they are powered, i.e DC motor and AC motor<sup>[4]</sup>. Additionally, names commonly known by people are such as synchronous motor, asynchronous motor, induction motor, reversible motor, stepping motor, servo motor, etc.

In terms of the common structure of different motors, they are generally composed of stator, rotor, commutator, air gap and windings, but they vary in size and layout of components. Stator, shown in Figure 2, as its name suggests, is stationary whichever state the motor is. It is made up of stator core, stator winding and engine base<sup>[5]</sup>. Rotor, opposite to stator in meaning, is the moving part inside the motor, propped up by bearings, shown in Figure 2. Commutator which is used on brushed DC motors is also



a moving part. With metal contact segments, its function is to keep the motor running continuously by reversing the direction of the current in each half. Air gap is the space between stator and rotor of a motor in which magnetic field is often created. Windings are wires laid out around either armature or stator. They are responsible for conveying current to achieve different purposes in different motors. For instance, in AC asynchronous, they can generate induced electromotive force when they are energized by current flowing through, whereby electromagnetic torque is produced.

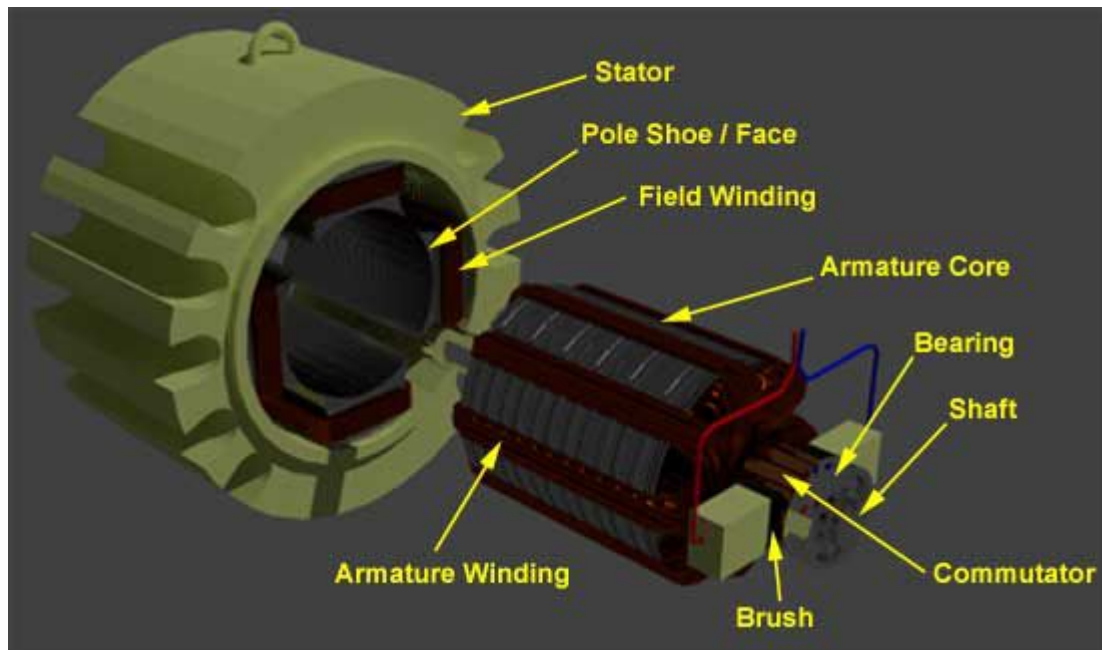


Figure 2 Common Structure of Motors<sup>[6]</sup>

### 2.2.1 Asynchronous Motor

Asynchronous motor is made up of two core parts, i.e, stator and rotor, with air gap between them. In addition, it also has cover, bearings, etc. Figure 3 shows structure of a typical asynchronous motor. For easy demonstration without losing generality, the following demonstration is based on a simple asynchronous motor shown in Figure 3.



Figure 3 Asynchronous Motor Structure<sup>[7]</sup>

### Stator

Stator cores shown in Figure 4 are part of the magnetic path for an asynchronous motor, with slots uniformly placed on the cores, which are used to place stator windings. The three-phase windings consist of three individual windings, i.e, A, B and C. Each winding is referred to as one phase. They are placed on six stator cores sticking out. When three-phase symmetrical current is introduced, stator windings can generate rotating magnetic field around the air gap.

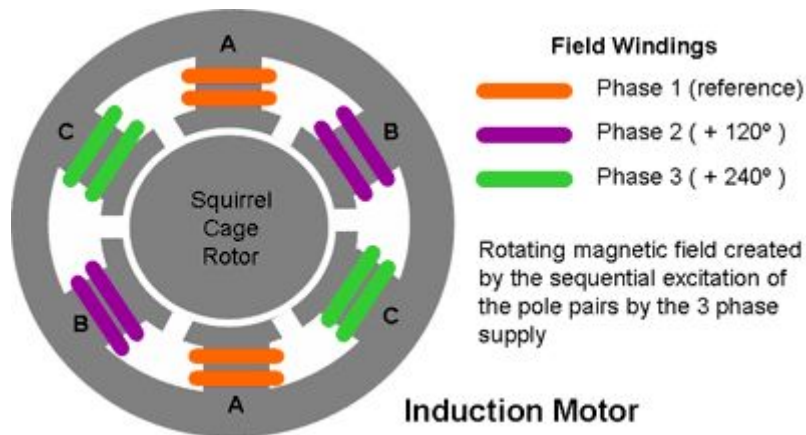


Figure 4 Stator and rotor of asynchronous motor<sup>[8]</sup>

### Rotor

Rotor core is placed through the shaft. It is, too, part of the magnetic path and is used to place rotor windings. Rotor windings are closed coils placed across the rotor core in which induced current can be generated by the rotating magnetic field discussed below.

### Rotating Magnetic Field

The reason the rotor of asynchronous motor can rotate and achieve energy conversion is the effect of rotating magnetic field created around air gap. When three-phase

symmetrical current is introduced to the three-phase symmetrical stator windings, a resultant magnetic field is created, which changes in its magnitude with time. The relations between the rpm  $n_1$ , frequency of the current introduced and the number of

pole pairs  $p$  is  $n_1 = \frac{60f}{p}$  [9]. This equation implies that the rpm of rotating magnetic

field is constant during operation under a given AC power source with a stable frequency upon construction of an asynchronous motor.

### Operation

The rotating magnetic field, generated by AC current introduced as input to stator windings, is cut by conductors as part of the closed windings placed on the rotor. According to Faraday's law, induced electromotive force is generated, and induced electromotive current is also generated since the rotor windings are closed. Assuming that at a moment the rotating magnetic field generated is rotating clockwise as shown in Figure 5, the induced electromotive force and current of each rotor conductor can be determined according to Ampere's rule.

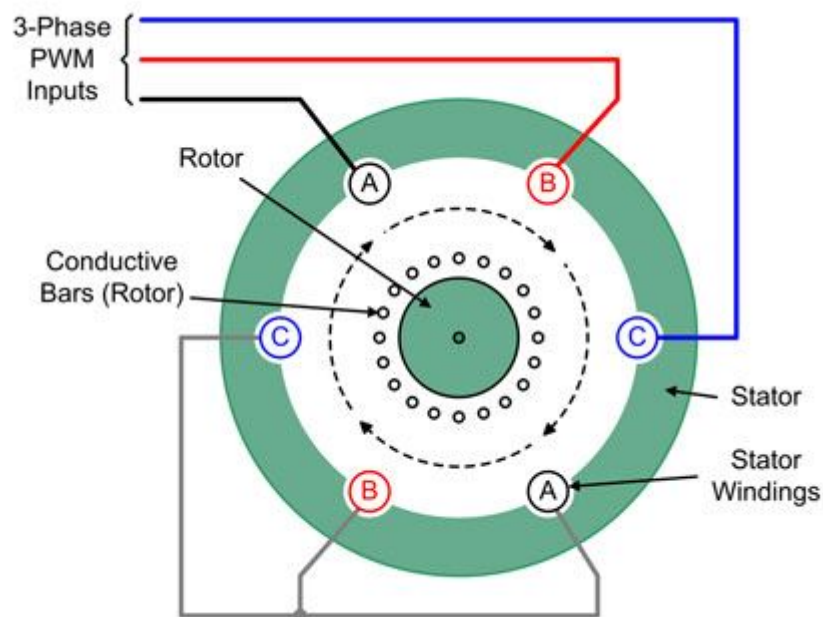


Figure 5 Rotating magnetic field<sup>[10]</sup>

The induced current generated combined with magnetic field create an electromagnetic force according to Ampere's rule, determined by the equation  $F = BLV$ , on rotor conductors and simultaneously generate a torque. Assuming this torque drives the rotor to rotate at rpm of  $n$  and therefore outputs a mechanical power. To ensure a continuous mechanical output generated of the motor, it is clear that the rpm of the rotor  $n$  must be less than the rpm of the rotating magnetic field  $n_1$ . It also can be inferred, based on the equation  $F = BLV$ , that the torque of the rotor is only

determined by the relative speed between the rotor and the rotating magnetic field in practical, since the velocity  $V$  in the equation is relative velocity. Figure 6 summarizes how asynchronous motor works.

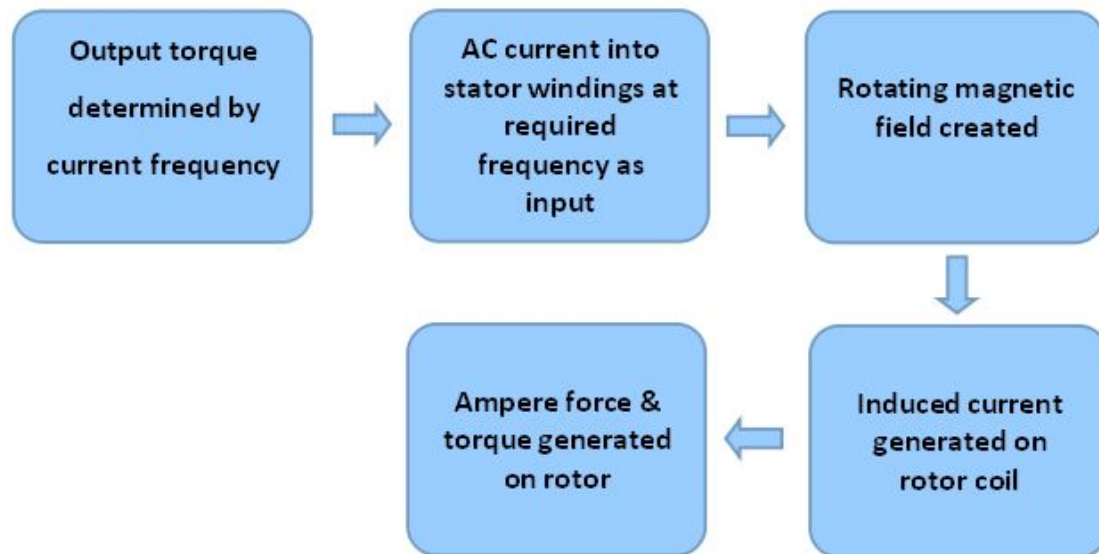


Figure 6

The equation which measures the revolutional slip between the rotating magnetic field and rotor is described by  $s = \frac{n_1 - n}{n_1}$  [11]. This can be used to analyze and calculate the

operating state as well as the mechanical characteristics of an asynchronous motor. For instance, the revolutional slip is approximately 0 when there is no load, increases correspondingly when load increases. Combining the torque equation and revolutional slip equation together, it can be inferred that the electromagnetic torque is only determined by the revolutional slip. A small revolutional slip results in a small output torque; a larger torque is generated by an increased revolutional slip. This characteristic determines some advantages enjoyed by asynchronous motors.

## 2.2.2 Asynchronous Motor Conclusion

Based on the analysis in the previous two paragraphs, the following benefits of using an asynchronous motor enjoyed by Jetski can be obtained.

1. The electromagnetic torque is determined only by revolutional slip, in other words, the electromagnetic torque remains unchanged so long as the revolutional slip remains unchanged under a given frequency of power source. For the Jetski project, given that the load, i.e, water will not change too much when operating the Jetski, the output of asynchronous motor used is determined only by the frequency of AC current as input which is adjusted by a motor controller according to the different throttle

levels.

2. According to the revolutionary slip equation and  $F=BIL$ , it can be concluded that an increased load results in a decreased rpm of the rotor, but meanwhile this will lead to an increased torque so that the Jetski will not lose speed significantly at the same throttle when load suddenly changes for various reasons

### 2.2.3 Synchronous Motor

Synchronous motors refer to motors where the revolving speed of the rotor is synchronous with the frequency of rotating magnetic field, regardless of loads connected to the motor. In other words, the revolving speed of the rotor  $n$ , the number of pole pairs of the rotor and the frequency of the rotating magnetic field  $f$  satisfy such equation:  $n=60f/p$ . Synchronous motors have many core components in common with asynchronous motors, i.e. stator, stator windings, and rotor. The main difference is the way by which the rotors are driven<sup>[12]</sup>. For easy demonstration without losing generality, the following demonstration is based on a simple synchronous motor shown in Figure 7.

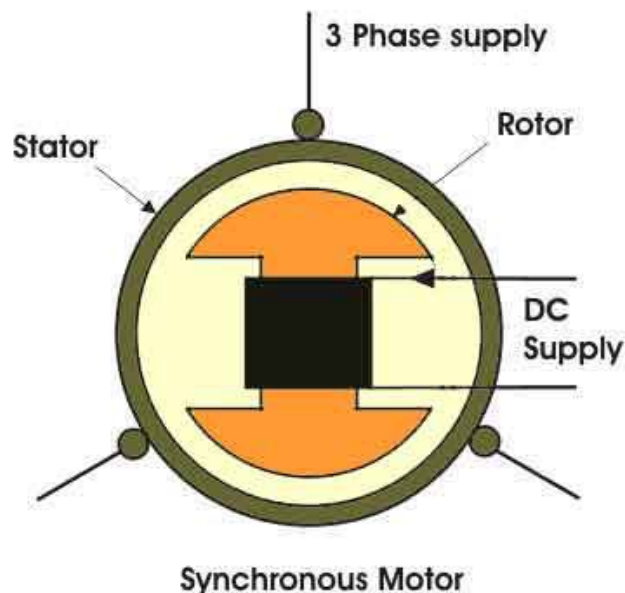


Figure 7 Synchronous Motor Structure<sup>[13]</sup>

#### Stator & Stator Winding

In terms of basic structure of stator, the difference is small between the stator of synchronous and asynchronous motors. It is made up of stator core, stator windings,

engine base, etc. Figure 8 shows a typical structure of a synchronous motor stator. The surface of stator core has slots evenly distributed in order to place stator windings across it. Stator windings, when a synchronous machine is used as a motor outputting mechanical power, are introduced with three phase symmetric current as input in order to generate a magnetic field around the air gap; otherwise stator windings serve as conductors to produce induced electromotive force and current when a synchronous machine is used as a generator.

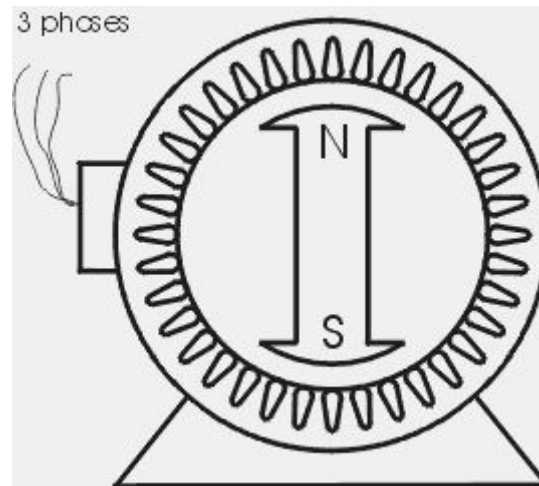


Figure 8 Stator Winding<sup>[14]</sup>

### **Rotor & Rotor Winding**

The rotor is built with two permanent magnet poles, i.e, N pole and S pole sticking out in these two examples shown in Figure 7 and Figure 8. The rotor windings are placed across the rotor and introduced with DC current either from rectified AC power source or from DC power source, regardless of the function a synchronous machine serves<sup>[15]</sup>. When introduced with DC current, rotor windings can produce a magnetic field, i.e, excitation field according to Ampere's Rule around the air gap, with its magnitude and direction both determined only by the DC current. This excitation field created reinforces the magnetic field produced by the two permanent magnet poles through the way the rotor windings are placed across the rotor and through the excitation field rotating at the same revolving speed as the rotor because the rotor windings are fixed across the rotor as shown in Figure 8.

### **Generator**

Synchronous machines can be used as generators<sup>[12]</sup>. This is achieved through following steps. The main magnetic field evenly distributed is created by introducing DC excitation current to the excitation windings placed across the rotor. The three phase symmetrical stator windings are used as power windings, conducting induced electromotive force and current generated. When the rotor is driven by external mechanical energy as an input, the main magnetic field created in the first step rotates with the rotor at the same speed. The conductor of the stator windings therefore cuts the main magnetic field periodically. As a result of this, induced electromotive force

which changes periodically in both magnitude and directions is generated in stator windings according to Faraday's law. And so long as the stator windings connected to outside circuits are closed, an induced current can be generated.

### **Motor**

When used as motors, synchronous motors are powered by magnetic torque generated which drives the rotor connected with load. A rotating magnetic field is created around the air gap when the three phase symmetric AC current is introduced to the stator winding. The rotor acts as a magnet when excitation DC current is introduced to the exciting winding placed across the rotor. Thus, a magnetic force, i.e. a torque is generated driving the rotor connected with load. Since this torque is generated by the effect of magnetic force, their revolving speeds remain equal, regardless of loads. In other words, a synchronous motor, when used to output mechanical power, rotates at a constant revolving speed  $n$  and therefore has a horizontal line in its mechanical characteristic curve.

## **2.2.4 Synchronous Motor Conclusion**

Given the constant revolving speed of the rotor when a synchronous motor is used to drive mechanical loads, synchronous motors are not suitable for vehicles of any kind. Jetski requires both flexibility and movability which are more determined by the characteristics of motor. From this respect, synchronous motors are unable to meet this requirement.

Another reason for not choosing synchronous motors is they are difficult to start<sup>[16]</sup>. When three phase symmetric AC currents are introduced to stator windings, the magnetic field created, i.e, rotating magnetic field rotates, with its revolving speed

determined only by  $n = \frac{60f}{p}$  [9]. The rotor, however, is unable to keep up quickly

with the revolving speed of the rotating magnetic field due to the effect of mechanical inertia. Thus, a relative movement occurs between the stator rotating magnetic field and the rotor. The torque generated around the air gap which drives the rotor is periodic and therefore is zero on average for a cycle. As a result, this torque can not power the rotor connected with loads to reach the synchronous revolving speed. Given this fact, to start a synchronous motor, solutions such as asynchronous starting method or variable frequency starting method are required[16], which adds both costs and complexity to situations where alternative motors are available.

The third factor against its suitability is the DC excitation source connected with rotor winding used to generate magnetic field. DC excitation source is complex in structure and expensive, often based on semiconductor switching circuit. For Jetski project, it is

better to limit the use of complicated control circuit with components which are vulnerable to vibration, temperature and humidity. Instead, in situations where motors of large capacity are required and with large investment, such as in power plant, synchronous machines used as generators should be first considered from an economical point of view.

## 2.2.5 DC Motors

DC motor, as its name suggests, refers to machines that can convert energy stored in DC current as input to mechanical power as output. Similar to AC motors in terms of structure, a DC motor is comprised of two major components - stator and rotor.

## 2.2.6 Brushed DC Motor

Before the advent of brushless motors, brushed DC motors used brushes to carry DC current as input. Figure 9 shows the structure of a typical and simple brushed DC motor. For easy demonstration without losing generality, the following demonstration is based on a simple brushed DC motor shown in Figure 9. Stator in Figure 9 is comprised of two permanent magnets which can be further powered by DC current in order to provide a stable magnetic field around the air gap. The two brushes are also parts of the stator. Between the two main poles are armature, with two conductors as parts of the armature coil. This coil has two cambered coppers connected which are mutually insulated, i.e. the commutators that are used to link the rotating armature coil with outside circuit.

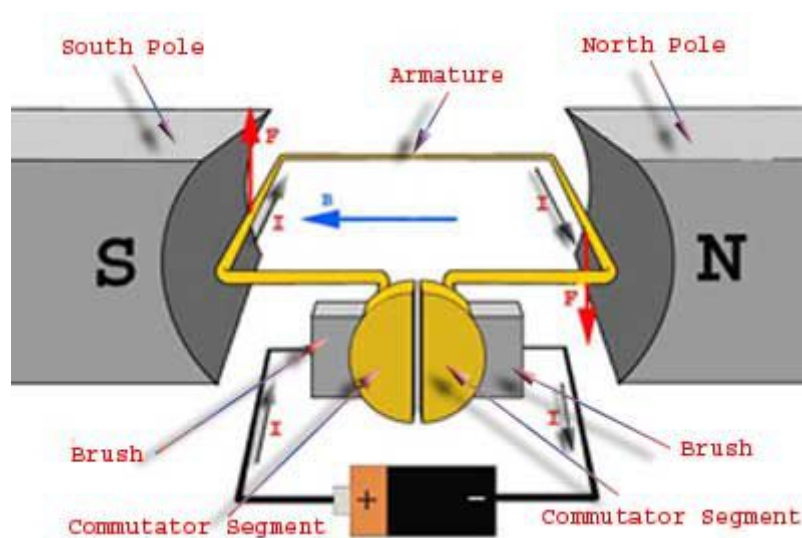


Figure 9 Brushed DC Motor Structure<sup>[17]</sup>



When the DC motor shown in Figure 9 is used to drive mechanical loads, the first necessary condition is to generate main magnetic field by the following method: DC current introduced to excitation windings placed across the stator cores or two permanent magnets as shown in Figure 9, such that the magnetic field generated is stable in both magnitude and direction in the air gap. Meanwhile, another DC current as the input needs to be introduced to the armature coil through two brushes. Without losing generality, assuming that this current is flowing in from the left brush and flowing out from the right brush. Ampere's force can be generated on both two conductors as parts of the armature coil, determined by  $F=BIL$ . The force on each conductor is equal in magnitude due to symmetry but opposite in direction, and the torque generated on each conductor, too, is equal in magnitude but opposite in direction, with its magnitude only subject to  $B$  according to  $F=BIL$  when these two parallel conductors rotate, given that the DC current and the length of two conductors remain unchanged. The torque of opposite directions on two parallel conductors ensures rotation of the rotor driving the load. When the two brushes swap positions as they rotate in each cycle, the overall torque generated on the armature coil remains unchanged in direction. Figure 10 summarizes how brushed motor works.

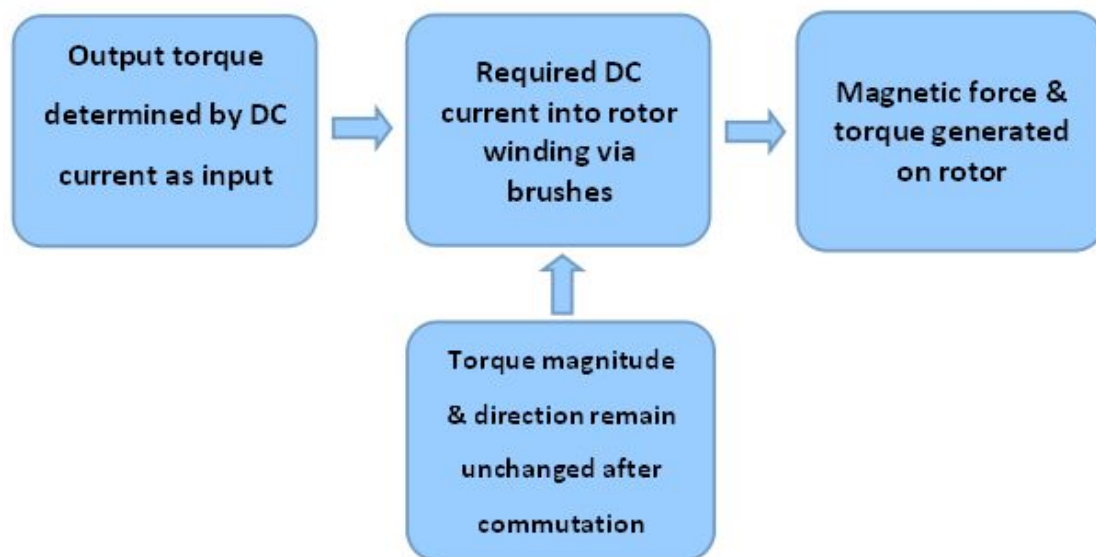


Figure 10

Based on the same principle, a brushed DC motor can have a stator with more than one pair of permanent magnets with excitation windings in order to overcome one disadvantage in the example above -- the torque generated is less continuous which occurs when two conductors are at the same horizontal plane where the magnitude of the torque on each conductor is zero. With more than one pair of permanent magnets added to brushed DC motor shown in Figure 9, the overall torque generated on the rotor will become more continuous, improving the performance of a brushed DC motor. Figure 11 gives an example of a brushed DC motor with more stator cores.

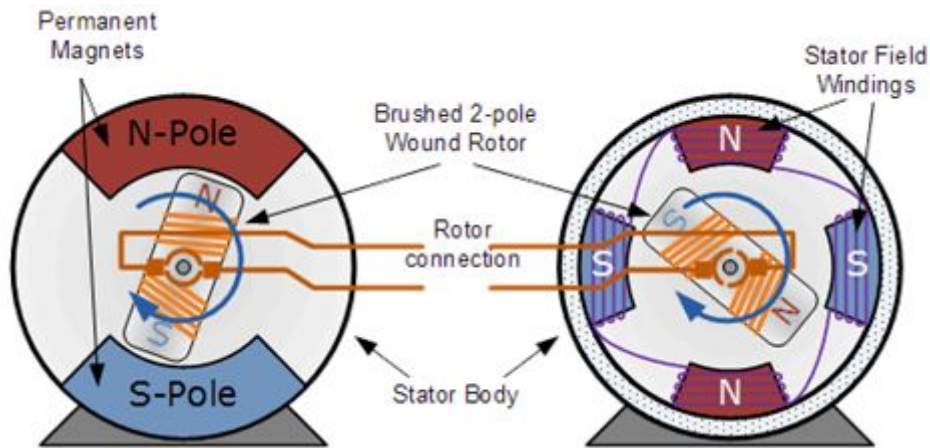


Figure 11 Brushed DC motor with more stator cores<sup>[18]</sup>

### 2.2.7 Brushed DC Motor Conclusion

As the two commutators rotate with armature coil, they alternately keep touching and the two brushes. This has a few negative implications. Carbon-made brushes are likely to become dangerously hot due to intensive use within short time; also likely to wear, as shown in Figure 12, due to long-term use which will further decrease efficiency of the motor and incur extra cost of maintenance and replacement<sup>[19]</sup>. For the Jetski project, given that the motor is installed in a cramped place where any maintenance or replacement of motor components is difficult to perform once upon installation, a sensible choice would be to seek alternatives with components of higher reliability and durability in order for convenience. The second disadvantage of brushed DC motors is that sparks are likely to occur between brushes and commutators<sup>[19]</sup>. For the Jetski project, given that the motor is installed close to the battery packs, there is every likelihood that sparks may cause serious consequences when the Jetski is running.



Figure 12 Worn brushes<sup>[20]</sup>

Notwithstanding, these two major disadvantages never negate one merit of brushed DC motors -- low cost which is later discussed. Contrary to brushless motors which feature more expensive semiconductor switching devices, brushed DC motors offer a cheaper alternative for situations where low cost is the priority. In addition, in situations where DC motors can be easily accessed for maintenance and replacement, brushed DC motors are a good choice.

### **2.2.8 Brushless DC motor**

Given that brushed DC motors utilize brushes for commutation thereby generating heat, causing sparks and having shortened life, brushless DC motors have been developed employing transistors to replace brushes<sup>[21]</sup>. As its name suggests, brushless DC motor does not have a brush. Rather, it depends on control circuit, i.e. semiconductor switching devices, e.g. GTR, MOSFET, IGBT, etc. to achieve the same function performed by brushes of brushed motor. With the exception of control circuits, brushless DC motors have the same structure as brushed DC motor, consisting of stator and rotor. For easy demonstration without losing generality, the following demonstration is based on a simple brushless DC motor shown in Figure 13.

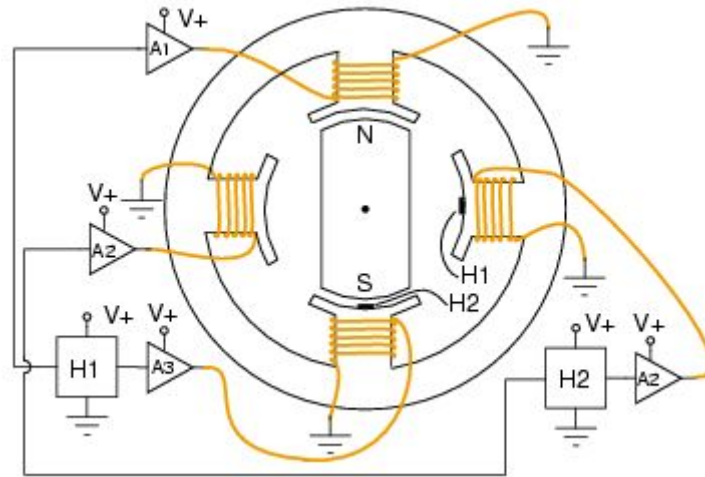


Figure 13 Brushless DC motor structure<sup>[22]</sup>

### Structure

The stator has four excitation windings placed across the stator cores, as shown in Figure 13. These four stator windings are used to generate 'rotating' magnetic field as the rotor rotates by introducing DC current as input. The stator windings are connected with switching devices V, part of the control circuit. The rotor has one pair of poles, i.e. N pole and S pole. It also has two position sensors built on the rotor detecting the position of rotor and sending electrical signals to the receivers built on the stator cores in order to control DC current introduced to the stator excitation windings. Given that the four stator cores with excitation windings are symmetric in space, only two position sensors shown in Figure 13 are sufficient for detecting the position of rotor.

### Operation

When DC current is introduced to any excitation windings across the stator core as input, a magnetic field is generated. Given that the rotor has only one pair of poles, a magnetic force therefore is created on the rotor, with the torque generated driving the rotor to rotate. Meanwhile, position sensors convert detected position signals to electrical signals in order to control switching devices, making sure that the torque generated is maximized and more continuous by introducing DC current to different stator windings according to position signals. For instance, when the rotor is in line with a pair of stator cores opposite to each other and is detected by position sensors, DC current as input should be introduced to the two excitation windings on this pair of stator cores by the switching devices connected with position receivers, such that the magnetic force generated on the rotor is maximized and so is the torque generated. As the rotor rotates and becomes in line with another pair of stator cores opposite to each other, the same process should repeat. Thus, the maximum driving effect on rotor continues as the DC current is in sequence introduced to the excitation windings on each stator core according to the position signals detected. Figure 14 summarizes how brushless motor works.

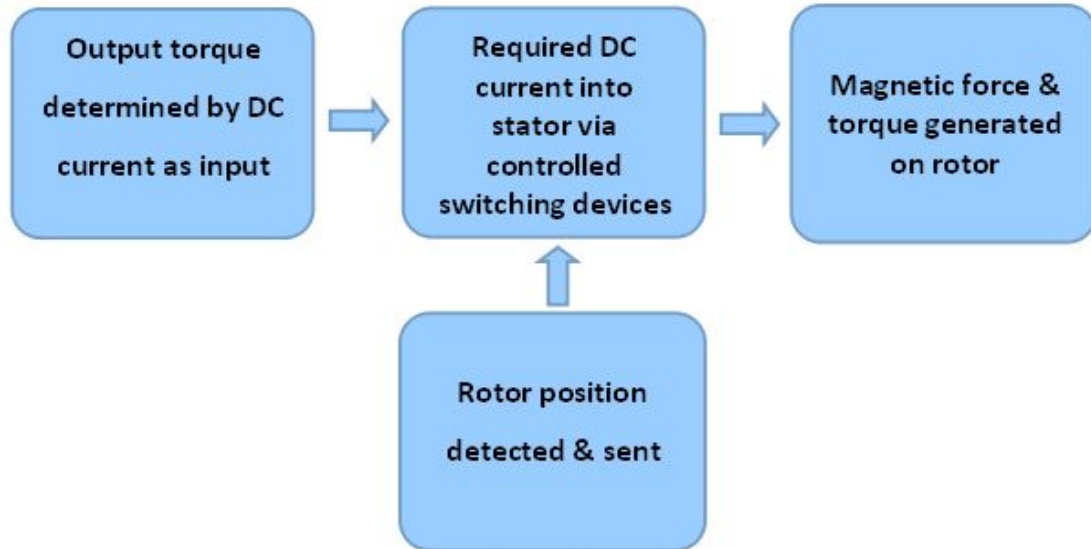


Figure 14

For more complicated brushless DC motor with improved performance, the rotor, based on the same principle, can have more than one pair of poles, e.g. two pairs of poles, while the stator can also have more pairs of stator cores with excitation windings placed across in order to maximize the use of magnetic field created simultaneously and to ultimately improve efficiency. Correspondingly, more position sensors and switching devices as part of the control circuit are required in order for preciser control of DC current introduced. With such complexity added to the brushless motor shown in Figure 10, the torque generated on rotor will increase and become more continuous, contributing to an increased efficiency and better performance.

## 2.2.9 Brushless DC Motor Conclusion

Given semiconductor switching devices used replacing brushes, it is easy to reap some benefits of using brushless DC motor for the Jetski project. First, brushless DC motors have longer lifetime than brushed DC motors because semiconductor switching devices never wear. Since the motor is installed in a cramped area in the Jetski, with more inconvenience for any maintenance and replacement of any motor component, high reliability and durability is important of motors considered. Second, semiconductor switching devices used in brushless DC motor eradicates sparks and many consequences associated which often occur during commutation process for brushed DC motor. For Jetski project, given that the motor is installed close to the battery of high voltage, eradicating the likelihood of sparks and associated damages to the Jetski is equally important. Third, semiconductor switching devices come with little physical contact with any other components of a brushless DC motor. This ensures high rotating speed of the rotor, which is suitable for Jetski where high speed, up to 8000 rpm, is required.

Despite these advantages, there are disadvantages against using brushless DC motor for Jetski project. The biggest concern is that position sensors with small signals are vulnerable to external disturbance, e.g. high temperature, damp or vibrating environment, etc, thereby causing inaccurate output which may trigger malfunction of motor. For Jetski, the motor is installed on the bilge therefore exposed to damp environment; and there is every likelihood that water seeps in, worsening the problem; the motor too is exposed to irregular vibration when operating the Jetski. These facts limit the use of brushless DC motor on Jetski in the first place. In addition, the use of position sensors and control circuit required adds both complexity and cost.

### **2.2.10 Motor Comparison Conclusion**

Based on theoretical analysis of the four categories of motors commonly used given the Jetski context, it can be concluded that asynchronous motor and brushless DC motor are more suitable for Jetski than synchronous and brushed DC motors. Asynchronous motor has its output only determined by the frequency of input current, it therefore has quick response to input change determined by the Jetski throttle. Brushless DC motor features electronic control circuits which eradicate danger during commutation process and ensure safe operation, though the use of sensors and switching devices vulnerable to harsh conditions may cause malfunction of motor.

# 3 Motor Selection

## 3.1 Motor Selection Background

Prior to specific search of different types of motors and comparison between them, two major requirements regarding motor selection need to be made. The first requirement is that motors to be considered for Jetski have to be suitable for the power of batteries already designed and chosen. The battery cell finally chosen for this project is Headway 10Ah LiFePO4 from EV WORKS. The nominal voltage of each cell is 3.2V. The maximum continuous discharge current is 30A, while the maximum peak pulse discharge current is 100A. 240 cells in total were purchased for the Jetski and grouped into 30 modules linked in series, with each consisting of 8 cells connected in parallel. Thus, a total voltage of 96V was formed to power the Jetski, with the maximum discharge current at 800A in theory. Given this fact, the motors considered are expected to be able to run under the following conditions -- around a nominal voltage at 96V and power less than  $96 \times 800 = 76.8\text{kW}$ . The second requirement is that motors to be considered are strongly recommended to be water cooled rather than fan cooled. This is due to the layout of many components in a cramped area where fan cooling is impracticable.

## 3.2 Asynchronous Motor Option

One asynchronous motor considered for the Jetski was from Submersible Motor Engineering PTY Ltd (SME), dedicated to design, manufacture and supply of submersible electric motors for special use and requirements<sup>[23]</sup>. The motor is shown in Figure 15 and some important information on this motor is given in Table 1.



Figure 15 Asynchronous motor selected<sup>[24]</sup>

Output Power	Nominal Voltage	Winding Connection	Number of Poles	Maximum RPM
50kW	96V	Wye	2	8000
Stator Phase Current	Rated Slip	Rated shaft speed	Input Power	Efficiency
369.366 A	0.02	7940 rpm	52.6kW	95%

Table 1 Asynchronous motor selected

From Table 1, this asynchronous motor has 24 and 28 slots for placing stator exciting winding and rotor exciting winding respectively. Given that the stator has 28 plots which are enough for generating a dense rotating magnetic field by introducing AC input current to stator winding, the number of rotor poles is less critical in generating torque. This asynchronous motor has a small rated slip at 0.02, which means the motor has a quick response to load change as well as to input change. The nominal voltage of 96V matches the battery voltage, while the rated input power of 52.6kW can be obtained from the battery with a maximum power of 76.8kW. More important is that its efficiency is up to 95% given the output power of 50kW, which complies with the belief of the RevProject -- building a zero carbon-emission Jetski.

### 3.3 Brushless DC Motor Option

One contrasting brushless DC motor considered available on the market as an alternative to AC motor for the Jetski is from 3xE - electric cars, who specializes in building electric drives for green-energy projects. The solution considered from this provider is a brushless DC motor which is cooled by water with an associated controller. The motor is shown in Figure 16 and some important information is given in Table 2.





Figure 16 Brushless DC motor considered<sup>[25]</sup>

Maximum Output Power	Nominal Voltage	Maximum Torque	Maximum RPM	Price
60 kW	288 V	250 Nm	4000	\$9,741.00

Table 2 60kW ELECTRIC MOTOR BLDC

According to the data sheet, this brushless DC motor has a peak power of 60kW and a nominal power of 30kW, both of which can be satisfied from the battery designed previously. However, its nominal voltage is three times as high as the nominal voltage of Jetski battery. Since the maximum torque of 250Nm and maximum RPM of 4000 can be obtained at the nominal voltage of 288V, the actual maximum voltage of 96V provided by battery will result in a significantly decreased maximum torque and RPM, affecting the performance of Jetski.

Another brushless DC motor of different rated values available from this provider is shown in Figure 17. It is also water cooled and has a lower maximum output power at 50kW but a much higher maximum speed at 9000rpm. These two critical indexes, however, hinges upon its rated voltage of 320V, higher than the first one. Given the motor will operate at a nominal voltage of 96V, neither maximum output power nor maximum speed will be as high as their rated values. Rather, there should be a significant decrease in both two rated values.



Figure 17 Brushless DC motor considered<sup>[26]</sup>

Apart from these two specific brushless DC motors discussed above, a series of alternatives are also found at Xinda Green Energy Co., Limited. This series includes high speed permanent magnet motors with output power ranging from 20kW to 60kW, which can be cooled either by water or air. The Table 3 gives some basic information regarding them.

Power	Rated Voltage	Max Speed	Peak Torque	Peak Power	Peak Current	Efficiency	Weight
20 kW	144V	3500rpm	140Nm	50kW	280A	94.7%	92kg
22kW	144V	3500rpm	150Nm	56kW	320A	94.7%	92kg
25kW	144V	3500rpm	170Nm	60kW	380A	94.8%	98kg
27kW	144V	3500rpm	180Nm	65kW	380A	94.8%	102kg
30kW	228V	3500rpm	200Nm	70kW	290A	94.5%	110kg
35 kw	228V	3500rpm	210Nm	75KW	350A	94.6%	114kg

Table 3 Parameters of 20kw-35kw BLDC<sup>[27]</sup>

From Table 3, it can be seen that the maximum output power of these brushless DC motors is no more than 75kW for each, thereby can be obtained from the battery. The rated voltage, however, is all beyond 96V, which will cause drop in both speed and output power. The efficiency is invariably high for each, similar to the two brushless DC motors above.

### 3.4 Brushed DC Motor Option

Brushed DC motors suitable for the Jetski or other electric vehicles are thin on the ground based on the writer's search results. This is due largely to the merits of using brushless DC motors, as discussed previously at section 2.2.8. For Jetski project, it not only requires values of some important parameters, e.g, output power, rated voltage, maximum speed being within an accepted range such that the motor considered is compatible with the Jetski power source, it also requires physical suitability of the motor so that it can fit into the Jetski. Based on the writer's search of commercially available brushed DC motors, a series of 50kW motors are selected for the purpose of comparison with other types of motors. Figure 18 shows a Z4 series motor and some basic information regarding this series is given in Table 4.



Figure 18 Brushed DC motor considered<sup>[28]</sup>

Output Power	Rated Voltage	Rated Power	Speed	Voltage	Prices
1kw -- 60kW	400V	50kW	750-- 3000 rpm	220V, 250V, 380V, 440V or...	\$1000 -- \$2000

Table 4 Parameters of Brushed DC motor

From Figure 18, it can be seen that brushed DC motor is more physically difficult to fit into the Jetski than brushless and asynchronous motors. It is therefore absolutely not the first choice for Jetski where most components, e.g, controller, DC-DC converter, heavy cables and pumps are all fitted into a cramped area. In addition, the voltage required is at least two times as high as the DC battery selected, which will

cause the same problem of output power drop as well as speed drop. And according to the writer's search of brushed DC motors, they are invariably fan cooled, which does not make for a good option for Jetski.

### **3.5 Synchronous Motor Option**

Since synchronous motors have a constant output speed as discussed previously at section 2.2.4, they are not ideal for being used as a motor for any vehicle requiring high manoeuvrability. The writer's further search on commercially available synchronous motors suitable for electric vehicles confirm this by having found few result as an appropriate contrasting example. Therefore, synchronous motors are not considered in this section from a practical point of view.

### **3.6 Motor Selection Conclusion**

To compare those motors mentioned above, some critical factors are taken into account, i.e, peak power, maximum speed, rated voltage and price. And it is important to draw conclusions on motor selection based on the following comparison results. The detailed information regarding comparisons is given in Table 5.

	Peak Power (kW)	Maximum Speed (rpm)	Rated Voltage (V)	Prices (AUD)
Asynchronous motor by SME	50	7940	96	—
Brushless DC by 3xE - electric cars	60	4000	288	9714 (Controller included)
Brushless DC seires by Xinda Green Energy Co	50~75	3500	144, 228	unknown
Brushed DC-- Z4 series	50	3000	400	1000~2000

Table 5 Comparison between motors considered

From Table 5, it can be seen that brushless DC motors manufactured by either 3xE - electric cars or Xinda Green Energy Co have low maximum speed compared with the asynchronous motor. Having considered their rated voltage is significantly higher than 96V at which the Jetski will run, their peak power and speed will drop to a even lower level as a result. As for brushed DC Z4 series, its actual performance is expected to be even worse than two brushless motors owing to the same problem. In terms of prices, Z4 series is typical of brushed DC motors which are the cheapest with motor controller excluded, whereas brushless ones are most expensive with motor controller included.

The asynchronous motor manufactured by SME provides much higher speed than any other motors, though its peak power is low. Its rated voltage of 96V matches the Jetski battery. Therefore, it is the most suitable motor for the Jetski as its high rated output power and high rated speed will not drop at rated voltage. And it is good for the Jetski project that the motor finally used was sponsored by SME at unknown cost. The only cost generated with this sponsored motor was on the purchase of an AC induction motor controller at around USD2000. Thus, the asynchronous motor manufactured by SME is both technically and economically practical for the Jetski.

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# Appendix A







## Appendix B

<b>Communication Cable</b>		
<b>Controller side -- Color</b>	<b>Description</b>	<b>Female Serial Port -- Color</b>
Pin 7 -- Black	GND	Pin 5-- Yellow
Pin 28 -- Red	TX	Pin 3 -- Red
Pin 29 -- White	RX	Pin 2 -- Brown
		Pin 7, Pin 8 connected
		Pin 4, Pin 6 connected
<b>Throttle Cable</b>		
<b>Controller side -- Color</b>	<b>Description</b>	<b>Throttle Box -- Color</b>
Pin 7 -- Black	GND	Brown
Pin 16 -- Green	Signal	Black
Pin 26 -- Blue	Vcc	Blue
<b>Encoder Cable</b>		
<b>Controller side -- Color</b>	<b>Connector</b>	<b>Encoder Cable -- Color</b>
Pin 7 -- Black		Black & Brown
Pin 26 -- Red		Red
Pin 31 -- White		Yellow
Pin 32 -- Yellow		Green

## Appendix C

<b>Safety System Connections</b>				
	<b>Cable A</b>	<b>Cable B</b>	<b>Cable C</b>	<b>Cable D</b>
<b>Pin 1</b>	Green & Shield	Blue	Orange	Green & Shield
<b>Pin 2</b>	Blue	Green & Shield	Blue	Blue
<b>Pin 3</b>	Orange	Purple	Brown	Orange
<b>Pin 4</b>	White	Brown	Green & Shield	Purple
<b>Pin 5</b>	Yellow	Black	Yellow	Yellow
<b>Pin 6</b>	Black	Yellow	Purple	White
<b>Pin 7</b>	Brown	Orange	Red	Brown
<b>Pin 8</b>	Red	Red	Black	Black

## Appendix D

<b>Important Controller Parameters Settings</b>	
<b>Name</b>	<b>Note</b>
Throttle	Type 2
Interlock Type	Type 2
Max Speed	8000 rpm
Main Enable	On
Pull In Voltage	80V suggested
Holding Voltage	75-80V suggested
Checks Enable	On
Nominal Voltage	96V
Forward Switch	4.5V < Pin 22 < 10V
Coil return	Pin 13 wired to positive side of the main contactor