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Capability Prediction of Lithium-ion Battery based on Analysis Main Characteristic of Direct Testing of Electrical Engine

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ABSTRACT

Lithium-ion batteries have been successfully used in electric machines by predicting battery pack capabilities based on the main characteristics produced. The research aims to analyze the capability of LFP lithium-ion batteries as the main electrical energy supply for electric machines. The focus of this research lies in the characteristic aspects of the battery assembly structure in the form of a 48V/20Ah (960 watt) cylindrical cell pack which varies the electric engine speed at 500 rpm, 1000 rpm, 1500 rpm, and 2000 rpm. The correlation between these two aspects influences the characteristics of the LFP lithium-ion pack battery. The method used is direct experimentation with a circuit set up connected to a propeller rotation load connected to the electric engine ass. The direct testing method on a BLDC electric engine is something new and has never been done before. Generally, testing is carried out in the laboratory using constant loading. Meanwhile, in direct testing, it is hoped that there will be fluctuations in loading which will indicate suitability when the battery will be implemented. The research results show that the LFP lithium-ion pack battery has several characteristics, including a voltage range of 55 V – 44.19 V. The resulting charging capacity is 33.44 Ah and the discharge capacity is 22.33 Ah. Experimental testing of electric machines shows that the battery experiences a voltage drop at the point 50 – 49.5 V; 49.5 – 49.0 V; 49.0 – 48.75 V. The voltage-current profile shows a decreasing transition in the initial voltage. In the range ≤ 47.0 V, the battery voltage-current will decrease quite significantly. The duration of use of the LFP battery pack depends on the rpm used; 500 rpm (33.47 hours), 1000 rpm (18.17 hours), 1500 rpm (13.3), and 2000 rpm (9.5 hours). The characteristics obtained are the main key in predicting the ability of LFP lithium-ion battery packs to supply electrical energy to electric machines.

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1. Introduction

The increase in carbon emissions from several types of vehicles is caused by the drive system still using internal combustion with a gasoline engine. This phenomenon occurs in land vehicles and sea vehicles. In marine vehicles in particular, the ICE concept is still often used by fishermen due to several mechanical and economic factors. The research results show that the use of gasoline as ICE fuel is because it is easy to find, relatively cheap, easily compressed by the spark from the spark plug [1].

The use of gasoline engines results in high exhaust emissions, high fuel consumption, and low lifetime using gasoline engines. Research about gasoline engine by Boretti [2] defined the weaknesses of gasoline engines can being resolved by developing electric engines. The use of electric engines and batteries, which have developed to date, can be used as one of the main alternative energy sources for fishing boats. Batteries are the most appropriate energy storage medium for use in all high-power EV vehicles.

Research on the use of batteries and electric engines in the marine sector was carried out on small boat specifications. Research by Reabroy *et al.,* [3], that a small boat requires electrical energy for the electrical propulsion system (EPS) which is supplied by 4 12V/120Ah accumulators and a 3-phase 2.2 kW electric motor. Lead acid type accumulator batteries act as a supply of electrical energy for electric motors. Other research by Sunaryo and Imfianto [4], concerns the use of electric engines in tourist boat sea transportation. The boat requires an average power of around 4 KW which is supplied from an accumulator battery in the form of a cylindrical cell battery of 144 cells with a total weight of 10 kg.

The use of electrical engines that have been developed in marine vehicles generally uses lead-acid secondary batteries in the form of accumulators or cylinder cells. Research by Albright *et al.,* [5], the type of secondary lead-acid battery used as an energy source has a strong acid content, is susceptible to corrosion, is relatively heavy, does not have a deep cycle, and has a low specific energy. The use of lead acid in previous electric engine research still had weaknesses in terms of the resulting electrochemical performance [6]. So, it is necessary to use other types of batteries to supply maximum electrical energy to the engine.

The lithium-ion battery that is widely used is the $LiFePO_4$ (LFP). LFP batteries have an olivine crystal structure with a theoretical capacity of 170 mAh at a voltage of 3.45 V in cell form and have a theoretical capacity of 1600 - 1800 mAh at a voltage of 3.2 V in cylinder cell form [7,8]. The current, voltage, and capacity characteristics of lithium-ion batteries can be increased in the form of LFP battery packs. In that form. LFP batteries can reach a working voltage of more than 12V with capacity variations of 5 - 100 Ah. Similar research by Oswal *et al.,* [9], batteries that have a large capacity can be applied as an electrical energy supply for electric engines.

Apart from being an energy source for the drive system, the LFP pack battery can be used as an energy source for the electrical system and as a place to store electrical energy during the charging process. In addition, Harjono *et al.,* [10] explained that batteries are used to supply electric current to run drives, lights, and other electrical components. According to the research by Abd Aziz *et al.,* [11], Li-Ion batteries are the best option in this category because to their low weight, large energy storage capability, moderate energy consumption, constant cost price reduction, advanced production technology, increased cycle life, and moderate energy consumption.

The main component in the EV drive system is the electric engine. The concept of an electric engine is that it gets energy from the battery through a controller that regulates the amount of power produced based on the use of the gas pedal. According to Azizi and Moghaddam [12], brushless DC (BLDC) electric engines are widely used to drive electric vehicles. The characteristics of an electric engine are that it has a rotor in the form of a permanent magnet and a stator in the form of a coil that can produce a magnetic field. BLDC electric engines have good efficiency, are more reliable, and have a long service life. About BLDC, Men *et al.,* [13] defined the hall effect sensor and rotary encoder components function to change the polarity of the BLDC motor electronically.

In the use of lithium-ion batteries in electric engines, there is a relationship between the power produced by the electrical energy source and the engine rotation (rpm) which shows changes in the resulting current, voltage, and usage time. Research by Mazlan *et al.,* [14] on variations in alternator rpm for battery charging systems in vehicles was carried out at variations of 750, 1500, and 3000 rpm. The research results show that the higher the engine speed, the greater the capacity produced by the alternator to charge the battery. If you use this principle, the change in engine rpm is directly proportional to the capacity produced. Other research by Mulyanto and Widagda [15] on the relationship between power and rpm was also carried out on modified generator engines with power variations of 120 – 720 watts. The research results showed that there had been fluctuations in engine rpm when operating at a certain power. Changes in engine rpm cause instability in the power supplied by the battery.

Based on the potential of lithium-ion batteries and the engine's ability to produce rotation, detailed research is needed that examines the relationship between LFP lithium-ion batteries based on the battery power used. This research aims to predict the capability to use lithium-ion batteries as an electrical energy supply in electric engines. The main characteristics of the LFP pack battery were analyzed based on the arrangement of the 48V/20Ah (960 watts) cylinder cell pack shape and variations in electric engine rotation of 500 rpm, 1000 rpm, 1500 rpm, and 2000 rpm. The selection of a lithium-ion battery is based on the battery's ability to supply an electric engine to produce a certain engine speed. The innovation in using lithium-ion batteries as a source of electrical energy for electric engines is expected to be able to realize zero emissions in electric fishing boats.

2. Methodology

The research method for predicting the capability of lithium-ion batteries uses experimental methods with direct testing of a 48V/2000W BLDC electric engine. The direct testing method on a BLDC electric engine is something new and has never been done before. Generally testing is carried out in the laboratory using constant loading. Meanwhile, in direct testing, it is hoped that there will be fluctuations in loading which will indicate suitability when the battery is implemented. This research was carried out in three stages to analyze predicted capabilities before being tested on fishing boat prototypes: (1) assembling a 48V/20Ah lithium-ion battery to obtain an electrical energy source, (2) designing an experiment with a BLDC electric engine, to obtain the correct circuit; and (3) testing at 500, 1000, 1500 and 2000 rpm, to analyze the capabilities of the lithium-ion battery that will be obtained.

2.1 Assembly Lithium-ion Battery Pack 48V/20Ah

The lithium-ion battery used in this research is a Lithium Ferro Phosphate (LFP) type battery. LFP batteries are assembled in series using 15 cylindrical cells connected in series to get a target of 48V and connected in parallel to get a target of 20Ah. Illustration of the LFP battery assembly arrangement in pack form in Figure 1. Battery specifications are to be used in Table 1.

Fig. 1. Battery LFP pack

Table 1
Specification of Battery LFP

Parameter	Value
Battery type	$LiFePO_4$
Configuration	15S 12P
Nominal voltage	48V
Capacity	20Ah
Weight	12 kg

2.2 Designing Experiments

Experimental design is a stage for assembling the LFP pack battery, DC Multifunction Tester, and electric engine components. The assembly process begins by identifying the positive pole and negative pole of each component. Furthermore, the positive pole of the LFP pack battery is connected to the positive pole of the electric engine, which is directly connected to the positive pole and the DC Multifunction Tester sensor cable. After that, the negative pole of the battery is connected to the negative pole of the DC Multifunction Tester. The output current on the red cable is connected to the negative pole of the electric engine. Illustration of the experimental design in Figure 2.

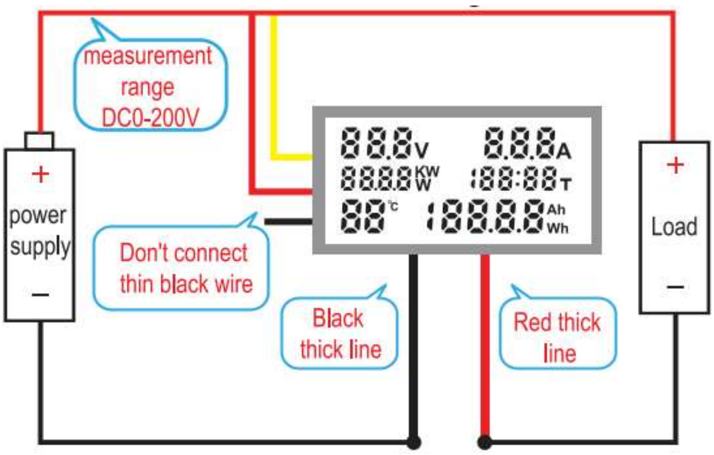

Fig. 2. Wiring diagram of experimental design

2.3 Experimental Testing

Based on the experimental design in Figure 3, the LFP battery pack that has been assembled and connected to an electric engine is then tested at rpm variations of 500, 1000, 1500, and 2000 rpm. Tests were carried out to determine the characteristics of lithium-ion batteries when combined with an electric engine. The tests carried out aim to obtain the main characteristics, including current, voltage, power, temperature, and usage time of the LFP battery pack. The main characteristics of the battery are recorded in real time using a digital DC Multifunction Tester, which is also recorded in real time.

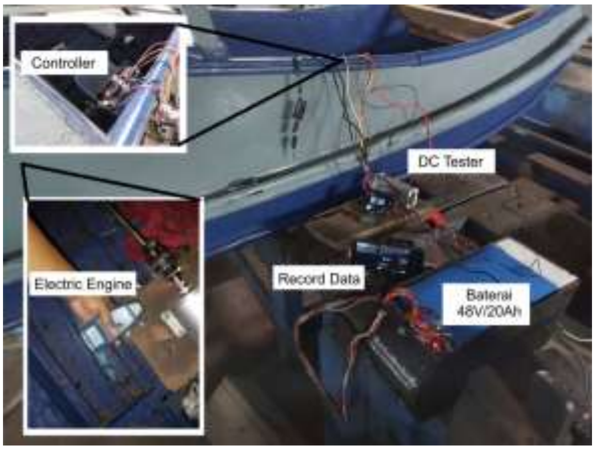

Fig. 3. Schematic of experimental setup circuit for lithium-ion battery with electric engine

3. Results
3.1 Analysis of Battery LFP Pack

Lithium-ion batteries are arranged based on series and parallel circuits, which form a battery in the form of a pack as shown in Figure 4. The results of the LFP pack battery assembly show that the battery is composed of cylinder cells with the code 15S12P. The code "15S" indicates that there are 15 series circuits and the code "12P" indicates that there are 12 parallel circuits. Based on calculations based on Eq. (1) until Eq. (3), the battery has a nominal value of 48V/20Ah. The battery testing process refers to ISO 18243 regarding lithium-ion battery testing procedures. Test procedures are used to determine characteristics critical to the performance, safety, and reliability of lithium-ion battery packs and systems. Information on measurement results can also be used to compare test results achieved on different battery systems.

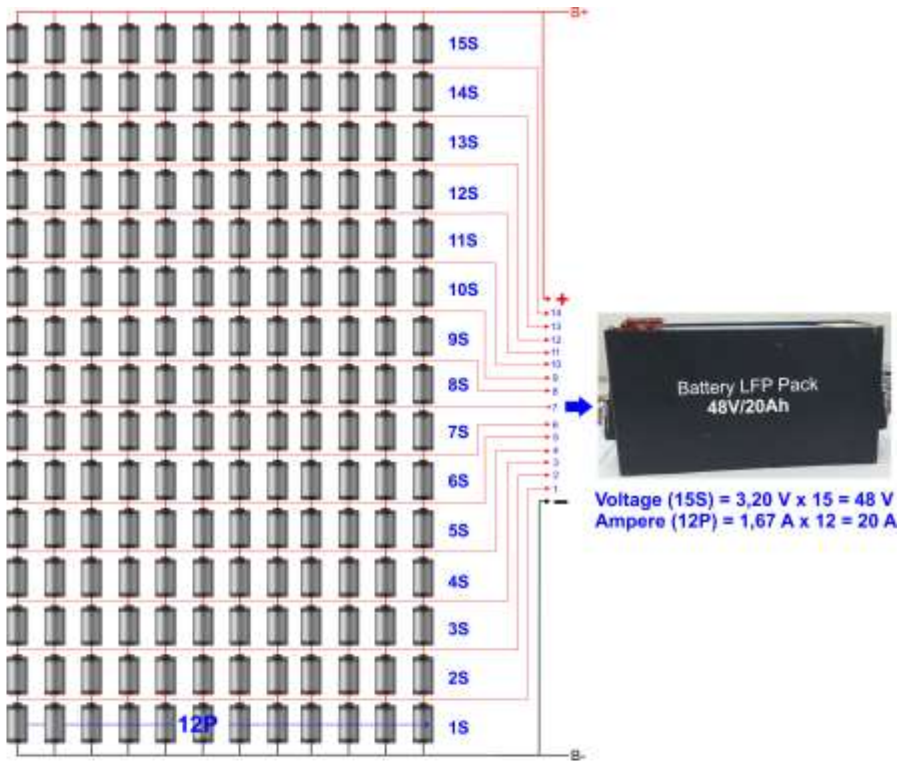

Fig. 4. Assembly diagram battery LFP Pack 48V/20Ah

Based on Eq. (1), the number of cylindrical battery cells in a series can be determined. Determining the voltage and ampere of the battery pack is calculated using Eq. (2) and Eq. (3) [16]

$$Battery\ series = \frac{motor\ voltage}{battery\ voltage} \tag{1}$$

$$Voltage\ \ pack\ battery = voltage\ cell \times seri\ series \tag{2}$$

$$Ampere\ \ pack\ battery = ampere\ cell \times\ parallel\ series \tag{3}$$

The battery LFP pack is then tested for performance test methods to determine energy and capacity at room temperature. Chaudhari *et al.,* [17] defined that energy and capacity at room temperature are carried out to measure the capacity of the DUT (Device Under Test) in Ah (ampere hour) units at a constant current rate. The testing process is carried out on a laboratory scale by determining a constant current, which has been adjusted to the measured capacity of C/3 in Ah units (Ampere hour). The test results are shown in Table 2. The consumption of electric power in BLDC motors can be calculated using Eq. (4) [16]. The current and working voltage parameters of the electric motor. on an electric motor with a voltage of 48 V and a working current of 5 A, the battery discharging time can be obtained as follows. With an 80% battery efficiency, the usage time will be

$$Disch\ time = 0{,}8 \times \frac{battery\, capacity}{working\, current} \tag{4}$$

Table 2
Main characteristics of battery LFP Pack 48V/20Ah

Parameter	Value
Battery type	$LiFePO_4$
Configuration	15S 12P
Voltage (V)	48V
Capacity (Ah)	20Ah
Weight (kg)	12 kg
Size (p × l × t) (cm)	37,5 × 21,5 × 17,5
Upper voltage (V)	55
Lower voltage (V)	44,19
Charger capacity (Ah)	33,44
Discharger capacity (Ah)	22,33
Charger Temperature (°C)	32,54
Discharger Temperature (°C)	31,31

3.2 Analysis of Main Characteristic on Electric Engine

Testing the battery directly on the electric engine can be used to identify the capabilities of the LFP pack battery as a source of electrical energy to operate the electric engine. Based on the initial test results, the main parameters obtained are shown in Figure 5. The characteristics of the battery voltage at each variation of 500, 1000, 1500, and 2000 rpm, experienced a decrease in voltage along with the length of the test time. These four variations have a similar graphic trend, namely experiencing several decreasing transitions at several points: (1) 50 – 49.5 V, (2) 49.5 – 49.0 V, and (3) 49.0 – 48.75 V. After passing these three points, the voltage will tend to decrease steadily. The decrease in voltage that occurs in the battery is correlated with the rpm of the electric engine and operational time. The higher the rpm value, the lithium ion battery tends to produce a large current. Meanwhile, the longer the battery is used in an electric engine, the resulting voltage will decrease. This is due to the phenomenon of intercalation and deintercalation of lithium ions in the inner circuit. The phenomenon that occurs is in accordance with research by Shu *et al.,* [18] shows that lithium ions will move back and forth within a certain period of time in the circuit and can cause a simultaneous decrease in voltage.

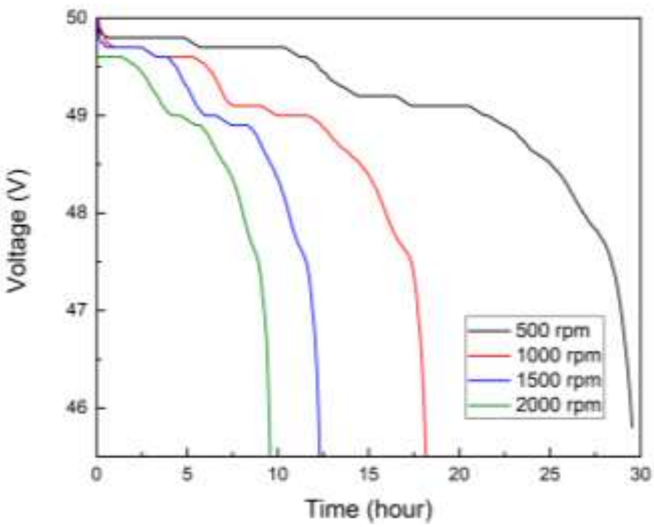

Fig. 5. Battery voltage at variations of 500, 1000, 1500, and 2000 rpm

Another parameter that can be used to identify battery characteristics is by the relationship between voltage (V) – current (A). Based on the initial test results, the relationship between the two parameters is shown in Figure 6. The characteristics of the battery current released at each variation of the electric motor rotation, 500, 1000, 1500 and 2000 rpm, decrease along with the decrease in battery voltage during operation. These four variations have a similar graphic trend, namely experiencing several decreasing transitions at several points in the initial voltage, while in the range ≤ 47.0 V, the voltage-current characteristics of the battery will experience a significant decrease. So, the battery will decrease its lifespan faster.

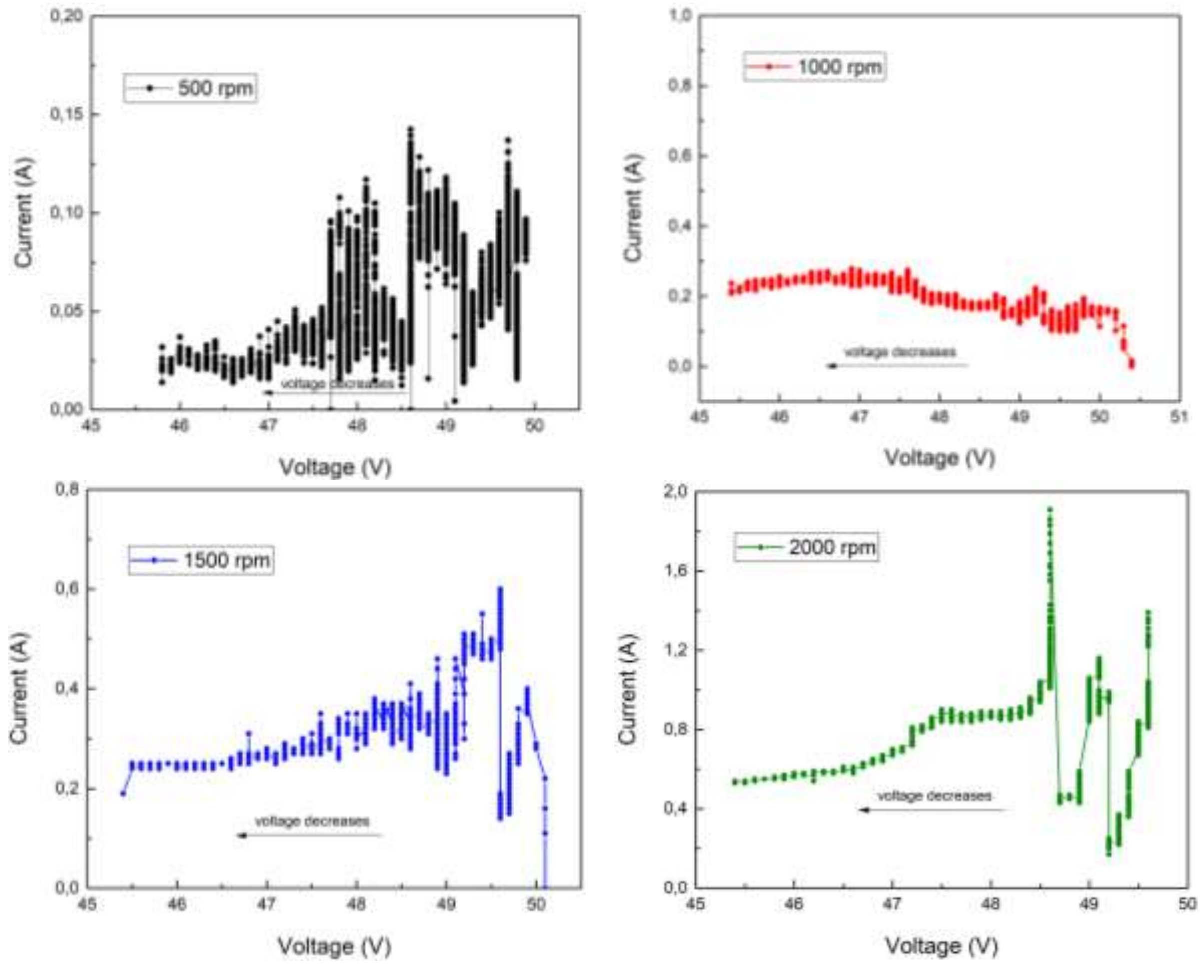

Fig. 6. Battery V-I relationship at variations of 500, 1000, 1500, and 2000 rpm

Based on Figure 5 and Figure 6, it can be concluded that the decrease in current-voltage that occurs is due to the gradual loading of the electric motor rpm. Increasing the rpm of the electric motor causes the battery to undergo a repeated discharge process quickly. Similar to research by Zhang *et al.,* [19], this results in changes in the crystal structure of the battery during the discharge process. Ion transfer during intercalation and deintercalation affects the energy capacity stored in lithium-ion batteries. Another factor that influences battery capacity is the number of lithium-ions stored in the two electrodes and how many lithium-ions can move during the charging and discharging process. According to Linden and Reddy [20], the amount of stored and distributed electron current is proportional to the number of moving lithium-ions. Test results can explain macroscopically the changes in voltage and current that occur during the testing process. The voltage and wear profile can be used as a reference in determining the capability of lithium ion batteries in electric engines.

The characteristics of lithium-ion batteries, which can be known based on equations, are power and capacity. Power characteristics can be determined using the voltage and current equations. Meanwhile, according to Yu and Jiang [21], capacity can be identified from the current that can be generated within a certain period of time. During the testing process, the motor rotation is set up with constant rotation at each rpm variation. Electric motors will experience rotation fluctuations due to changes in the electrical energy supply to the electric engine. The test results are shown in Figure 7.

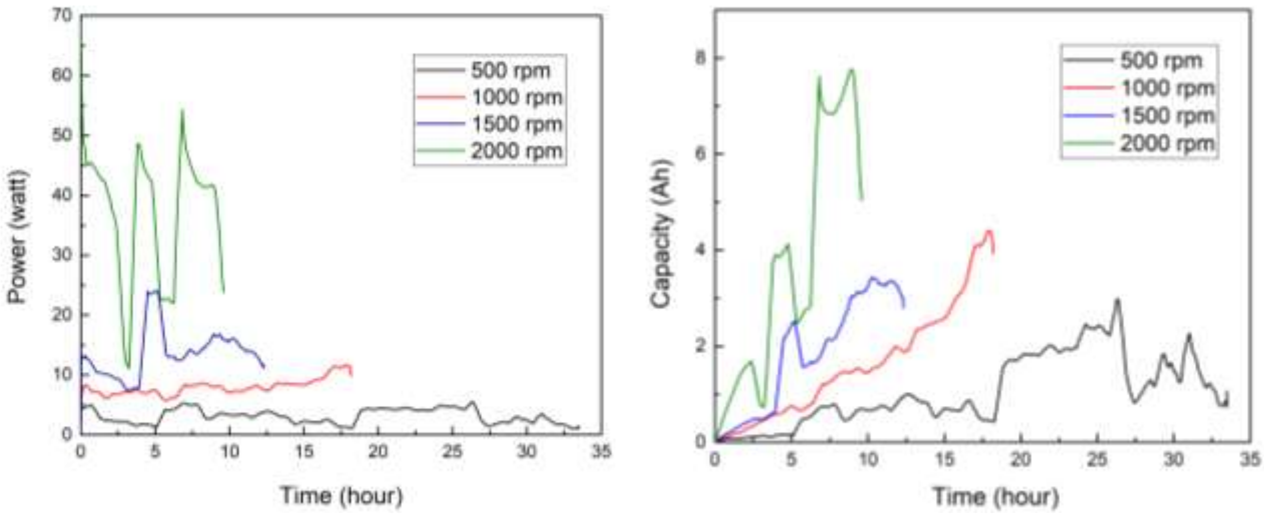

Fig. 7. Battery voltage at variations of 500, 1000, 1500, and 2000 rpm

In Figure 7, the power and capacity characteristics of a 48V/20Ah lithium-ion battery are shown at each rpm variation. Based on the calculation results, power and capacity fluctuations are influenced by the current flowing in the circuit. Higher rpm variations cause the lithium-ion battery to supply more power [22]. An electric motor is an electrical machine that converts electrical energy into mechanical energy. Most electric motors operate through the interaction between the motor's magnetic field and the electric current in the coil of wire to produce a force in the form of torque that is applied to the motor shaft.

The results of the evaluation of the main stress and the V-I relationship are closely related to the test method directly at each rpm variation carried out. This method can provide predictions of voltage, current, capacity and power in determining the ability of lithium ion batteries to support electric engines. The method used by Liu *et al.,* [23] show the proposed method can only use the previous charging curve of one cell in the pack and the current charging data of the battery pack to rapidly estimate the capacity of each cell in the battery pack.

Lithium ion battery testing on a 48V/2000 W electric engine is a direct test using new battery samples assembled based on the needs of the electric engine. Testing at rpm variations is focused on getting the main profile of the battery during use. Meanwhile, when the battery has entered the retired batteries category, the research method is used by Sun *et al.,* [24] which shows that a fast capacity estimation using incremental capacity and Gaussian process regression is proposed. Our results show high efficiency and accuracy of the proposed method.

Utilization of lithium ion batteries as a source of electrical energy in BLDC 48V/2000W, shows a long operating period. Figure 8 shows the relationship between rpm variations and the length of time the battery can supply electrical energy to the electric engine. Battery operating time is categorized based on rpm variations on the electric engine, including: 500 rpm (33.47 hours), 1000 rpm (18.17 hours), 1500 rpm (13.3), and 2000 rpm (9.5 hours). The characteristics of the battery usage time for each rpm variation show that it decreases as the duration of battery usage increases during operation. This is influenced by the decrease in current and voltage that occurs in the battery. At high rpm, the battery will tend to run out quickly during the emptying process. In direct testing, changes in rotation of the propeller ass can also be observed. This phenomenon can be used as a reference in determining the main electricity needs of an electric fishing boat. Research variation rpm by Mazlan *et al.,* [14] show that the higher the engine speed (rpm), the greater the capacity produced by the alternator to charge the battery. If you use this principle, the change in engine rpm is directly proportional to the capacity produced. Other research about power and rpm by Mulyanto and Widagda [15] show the correlation between power and rpm. The research results showed that there had been fluctuations in engine rpm when operating at a certain power. Changes in engine rpm cause instability in the power supplied by the battery.

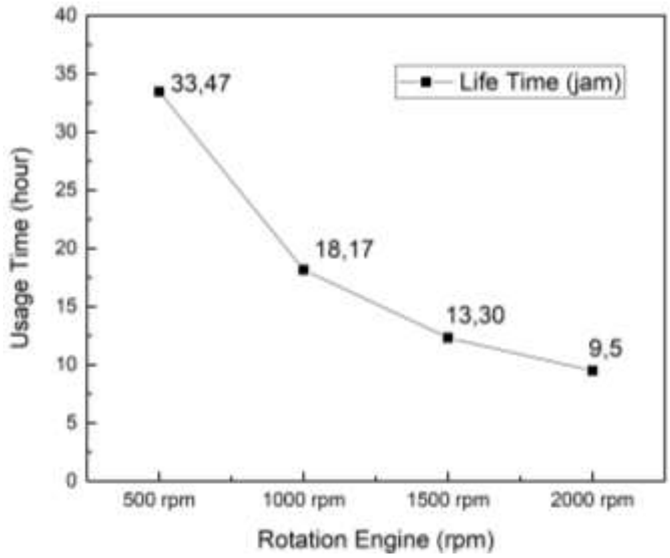

Fig. 8. Battery life time at variations of 500, 1000, 1500 and 2000 rpm

4. Conclusions

Lithium ion batteries have been proven to be used as the main source of electrical energy in vehicles that use an electric engine as a drive system. In this research, a type of BLDC 48V/2000W electric engine drive system has been tested which can be operated with a 48V/20Ah LFP lithium-ion battery. The main electrical needs of the vehicle can be met with 15 series circuits and 12 parallel circuits with the 15S12P configuration. Lithium ion battery with a weight of 12 kg, has the characteristics of an upper voltage of 55 V, a lower voltage of 44.19 V, a charging capacity of 33.4 Ah, a discharging capacity of 22.3 Ah. The ability of lithium ion batteries as a source of electrical energy can be determined by directly predicting the characteristics of the battery resulting from experiments. Direct testing on a BLDC electric engine is something new and has never been done before. Battery capability testing is generally carried out in the laboratory using constant current loading and discharging. Meanwhile, in direct testing, variations of 500 to 500 s.d. 2000 rpm (500 intervals) with propeller ass rotation loading. These four variations have a similar graphic trend with a decreasing transition at several points: (1) 50 – 49.5 V, (2) 49.5 – 49.0 V, and (3) 49.0 – 48.75 V. After passing these three points, the voltage will tend to continue to decrease. Then the V-I correlation has a similar graphic trend, namely experiencing several decreasing transitions at several initial voltage points, while in the range ≤ 47.0 V the battery voltage-current characteristics will experience a significant decrease. So, the battery life will decrease faster. Lithium-ion batteries have a long service life based on the engine speed used; 500 rpm (33.47 hours), 1000 rpm (18.17 hours), 1500 rpm (13.3 hours), and 2000 rpm (9.5 hours). There needs to be additional parameter observations to determine the performance of the lithium ion batteries to electrical fishing boat.

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