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Study of Battery Performance Analysis with Regenerative Braking Methods using SIMULINK

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Abstract. The purpose of this study is to find the most eligible battery capacity for ultra-compact electric vehicle. Lithium-Ion batteries configuration is designed and examined for the research. Physical characteristics of the vehicle and motor assign battery capacity. The battery must be able to attain certain length of track and to utilize regenerative braking method. Designed battery will be examined by adjusting loading variations and regenerative braking method with specified track length. The performance of the battery is analyzed with and without controller used during certain experiments. The obtained results emphasize the designed battery performances throughout variations of loading and regenerative braking method applied. During performance test in the field, the battery shows that the average discharge current is inversed to the average voltage during constant and varied velocity tests. Moreover, the battery velocity rises when the regenerative braking method is applied. The throughout experiment will be compared and analyzed using SIMULINK.

1. Preliminary

Electric-powered vehicles or electrical vehicles are expected to be able to match the performance of fossil-fueled vehicles in their development. This performance is usually seen from the ability of acceleration, speed, fuel costs, distance that can be taken, purchase prices and maintenance costs. The cost per kilometer of energy needed to drive an electric vehicle is cheaper than the cost per kilometer of energy used to drive gasoline-powered vehicles. However, the energy of electrical vehicles should be stored in batteries that can be recharged (*recharge*). Until now there is no type of battery that is able to fulfill all of the above mentioned performance [2].

The *lithium-ion* battery is a lithium-based battery that is currently commonly used in electrical vehicles [2]. Lithium-based batteries have the advantage of several technical parameters such as energy density, energy efficiency, life cycle, and good *C-rate* when compared to other types of batteries [3, 4]. This prompted the author to conduct research on the analysis of *lithium-ion battery performance* on the KARLING prototype for short distance use.



2. General Definitions of Batteries and Motor Brushless Direct Current (BLDC)

2.1. Cell and Battery Components

A battery consists of one or more cells connected in series or parallel or even both. This depends on the desired output voltage and battery capacity. Cells are basic electrochemical units that produce electrical energy sources by direct conversion of chemical energy. A cell consists of three main components, namely [3]:

- Anode or negative electrode that releases electrons to the external circuit and is oxidized during electrochemical reactions.
- The cathode or positive electrode that receives electrons from the external circuit and is reduced during the electrochemical reaction.
- Electrolytes that provide a medium for the transfer of charges, such as ions, inside cells between anodes and cathodes.

2.2. Cell and Battery Classification

Electrochemical cells and batteries are identified as primary (not rechargeable) or secondary (rechargeable), depending on their ability to be electrically recharged [3]. With this classification, other classifications are used to identify specific structures or designs. In general, cells or batteries are classified into 4, namely primary, secondary, back-up and fuel cells.

2.3. Cell Operations

Cell operation that occurs on the battery is divided into two, namely the usage conditions and charging conditions. Usage conditions or commonly called discharge conditions. At the time of the cells connected to the external load, electron flowing from the anode, which has been oxidized, to the cathode through an external load. The electrons are received by the cathode and the cathode material is reduced. The electrical circuit is finished in the electrolyte with the flow of anions (negative ions) and cations (positive ions) to the anode and cathode, respectively.

While the charging condition is usually called the charge condition. During recharging of rechargeable cells or storage cells, the current flow is opposite. Oxidation takes place at the positive electrode and the reduction in the negative electrode. If the initial definition of anode is where oxidation occurs and the cathode is the place where the reduction occurs, then the positive charge electrode is the anode and the negative is the cathode.

2.4. Brushless Direct Current Motor (Brushless Direct Current Motor)

Brushless direct current motor or commonly called BLDC (*Brushless Direct Current*) motor is an electric motor with a direct current source of which in running the process does not use a brush (*brush*) but electronically by utilizing feedback from the rotor position by the sensors [4].

2.5. Regenerative Braking Controller

Regenerative braking is one of the method that utilizes mechanical energy to be converted into electrical energy. The electrical energy produced during the braking process will be used for charging the battery. This method is one of the right methods to improve the performance of electrical vehicles. Regenerative braking transforms the motor into a generator by changing the motor's turning angle. The rotating motor at the positive rotational angle is supplied with a negative rotating angle resulting in an induction voltage greater than the voltage in the rotor. This voltage difference will be used for battery charging.

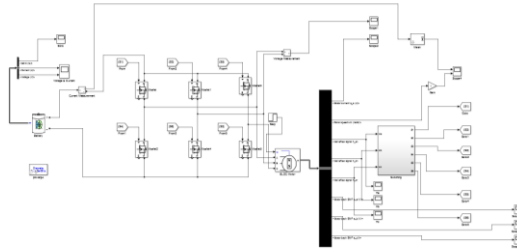


Figure 1. Simulink block diagram of motor controller.

3. KARLING Research and Design Planning

3.1. Research Flow

In this study two types of tests will be conducted to see the performance of the KARLING battery, which is testing the characteristics of battery charging / discharging and testing on the vehicle.

The first step in doing this research is to determine the concept of environmentally friendly vehicles (in this study will be called KARLING) that will be designed.

Table 1. KARLING Framework Concept Specifications

Maximum Vehicle Length	2.5 m
Maximum Vehicle Width	1.5 m
Maximum Vehicle Height	2.5 m
Minimum Axis Distance	1.5 m
Minimum Land Distance	0.25 m
Maximum Vehicle Weight (without driver)	150 kg

After determining the concept of KARLING, the next step is to determine motor and controllers specifications with a mathematical approach based on data obtained through literature studies. The next step is to design the battery pack by considering the usage time, power requirements, and security of the battery pack. The battery pack that has been designed is then tested first to see the charging and discharging characteristics. The data obtained is then processed and analyzed. The next step is to carry out mechanical design including the shape of the vehicle frame, placement of the mounting (mounting) motor, controller and battery. The next stage is to test the battery performance of the vehicle with several test scenarios. From the test results obtained data must be processed and analyzed to determine the performance of the battery pack on the vehicle. The last stage is drawing conclusions from the research that has been done.

3.2. Mechanical and Simulation Design

The design is then simulated with 150 kg loading. The simulation is a displacement test using an Autodesk inventor application. Loading is done at the point of the passenger sitting. From the simulation results it can be seen that the biggest shift that occurs in the frame is 0.0228 mm. This result is very good and it can be concluded that the KARLING frame is safe to use. Simulation results can be seen in Figure 2(b).

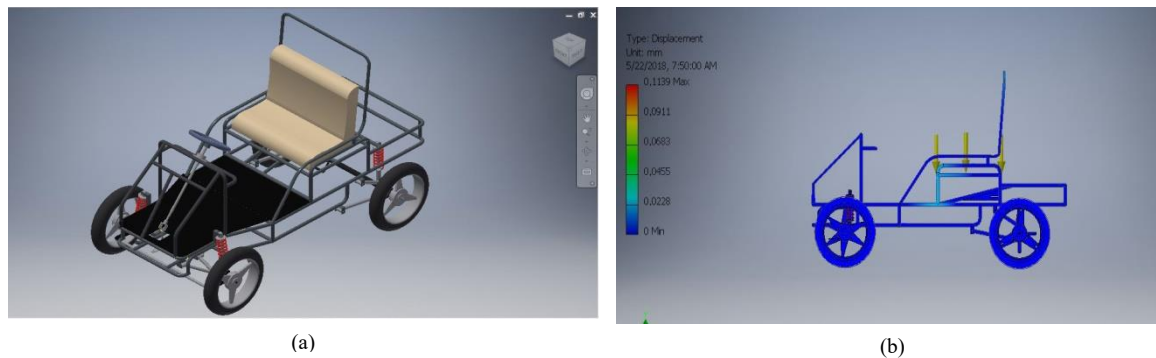


Figure 2. (a) KARLING Mechanical Design (b) *Displacement Test Simulation Result Using Autodesk Inventor*

3.3. Calculation of KARLING Energy Needs for Short Distance Use in the University of Indonesia Campus Environment

To find out the power requirements needed by KARLING, you must know the forces that work on KARLING. These forces include wheel friction, air friction force, acceleration force and gravitational force. So that the total force can be written through the following equation:

$$F_{total} = C_{gr}N \cos \theta + \frac{1}{2} \rho v^2 C_{gu} A + ma + mg \sin \theta \quad (1)$$

Table 2. KARLING Design Parameters

C_{gr}	0.02
m	250 kg
g	9.84 m / s ²
ρ	1.18 kg / m ³
C_{gu}	0.38
A	1.18 m ²

From the substitution of the KARLING parameter values in Table 3 to equation (1), the total force equation is obtained as a function of the velocity as follows:

$$F_{total}(v) = 49,2 \cos \theta + 0,264 v^2 + 250 \frac{dv}{dt} + 2460 \sin \theta \quad (2)$$

From equation (2) then multiplied by the wheel radius (0.1778 m) so that the following equation is obtained:

$$\tau_{tire} = 8,748 \cos \theta + 0,047 v^2 + 44,45 \frac{dv}{dt} + 437,388 \sin \theta \quad (3)$$

To obtain the magnitude of motor torque, equation (3) is multiplied by the ratio of the KARLING gear (35:31) assuming mechanical losses of 20%. So that the following equation is obtained:

$$\tau_{motor} = 11,85 \cos \theta + 0,064 v^2 + 60,22 \frac{dv}{dt} + 592,59 \sin \theta \quad (4)$$

Motor angular acceleration can be found with the following equation:

$$\omega_{motor} = 4,981 \times v \quad (5)$$

By multiplying equation (4) and (5), the power requirements for the input of KARLING will be obtained and are written as follows:

$$P_{input} = \tau_{motor} \times \omega_{motor} \quad (6)$$

The constant velocity maintained by KARLING on a horizontal track is 30 km / h or 8.33 m / s. The assumption of the time required by KARLING to reach a constant speed is 20 seconds with an initial speed of 0 m / s for a horizontal track so that the acceleration value of 0.416 m / s² is obtained. The acceleration value is ignored when the vehicle reaches the expected speed so that the speed is considered constant after the first 20 seconds. From this assumption, a velocity graph with respect to time is obtained as shown in Figure 3.

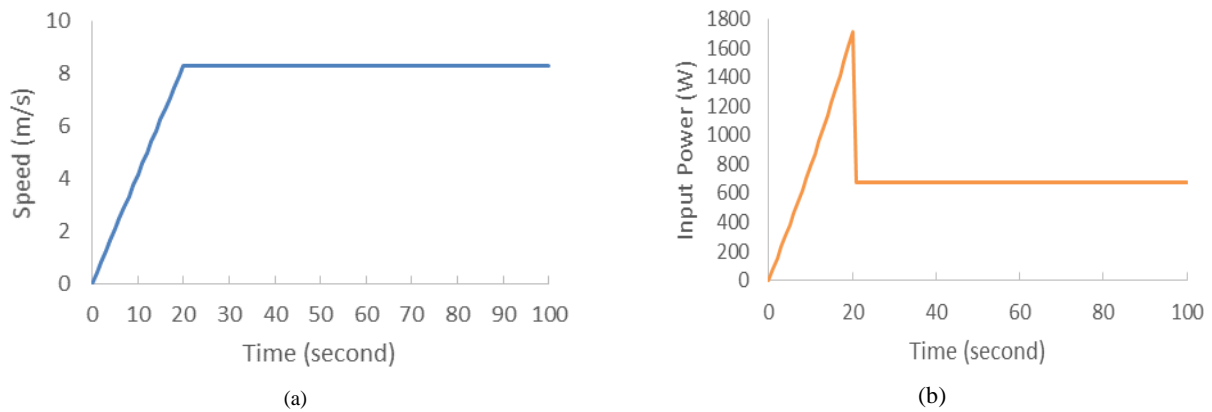


Figure 3. (a) Constant current charging 2 Ampere Graph (b) Charging Chart of 5 Ampere Constant Current

From Figure 4 it can be seen that the amount of energy required by the motor to move from stationary condition to 30 km / hour is 4,752 Wh. From the graph, the energy equation needed by KARLING is obtained by multiplying the input power with time so that the following equation is obtained:

$$E_{input} = \sum_0^t P_{input}(t) \times \frac{1}{3600} \quad (7)$$

Table 3. KARLING Testing Calculation on Track

Slope Percentage (%)	Tilt Angle (°)	Track Length (km)	Travel Time (seconds)	Power Needs (Watts)	Energy Needs (Wh)
1.06	0.61	0.164	20	937,857	5,21
1.44	0.82	0.312	37	1027,955	10,565
0.9	0.56	0.066	8	916,404	2,036
2.48	1.42	0.164	20	1285,312	7,141
1.65	0.94	0.164	20	1079,435	5,997
2.77	1.59	0.312	37	1358,209	13,96
2,3	1.32	0.23	28	1242,427	9.66
4.52	2.59	0.23	28	1786,784	13,897
3.59	2.06	0.328	39	1559,691	16.9
0	0	2,081	250	676.09	46.95

3.4. Battery Pack Design

It is known that the minimum energy required by KARLING is 137.068 Wh so that the average discharge flow is 20.27 Ampere. For this study the duration of use determined is about 1 hour. From the results of calculating specifications and timing of the load usage can be determined the value of battery voltage, battery capacity and maximum current that can be held by the battery. So the KARLING battery is designed with the final specifications as in Table 4.

Table 4. KARLING Battery Specifications

Number of Parallel \times Series	13S \times 8P
Maximum Continuous Discharging Flow	160 A
Maximum Charging Current	8 A
Nominal capacity	20 Ah
Nominal Voltage	48 V
Nominal Energy Capacity	960 Wh
Final Discharge Voltage	39 V
Charging Voltage	54 V
Standard Charging Flow	1 Ampere

4. Testing and Analysis Result

4.1. Constant Current Charging Test

KARLING battery charging test is carried out by two types of testing, namely charging with a constant current of 2 Ampere and 5 Ampere. It is known that the nominal capacity of the battery is 20 Ah with an energy capacity of 960 Wh. In the BMS specification used, the DOD allowed is 85% of the maximum capacity. So that the capacity of the battery that can be used is 17 Ah with an energy capacity of 816 Wh.

The test results with a constant current of 2 Ampere indicate that the capacity that can be charged to the battery is 16.92 Ah with the usage of energy 842.31 Wh with a time of charging of 9.54 hours. Nominal energy capacity that can be loaded from the battery is 816 Wh, so that the efficiency of charging using a constant current of 2 Ampere is 96, 88%. The difference between the input and output power occurs because the average voltage value of the test results is higher than the nominal voltage of the battery which is 49.86 Volts. The difference in the filling time of the calculation results with the test results occurs because the average charging current during testing is 1.81 Ampere. The charging characteristics graph to time of the test results can be seen in Figure 5.

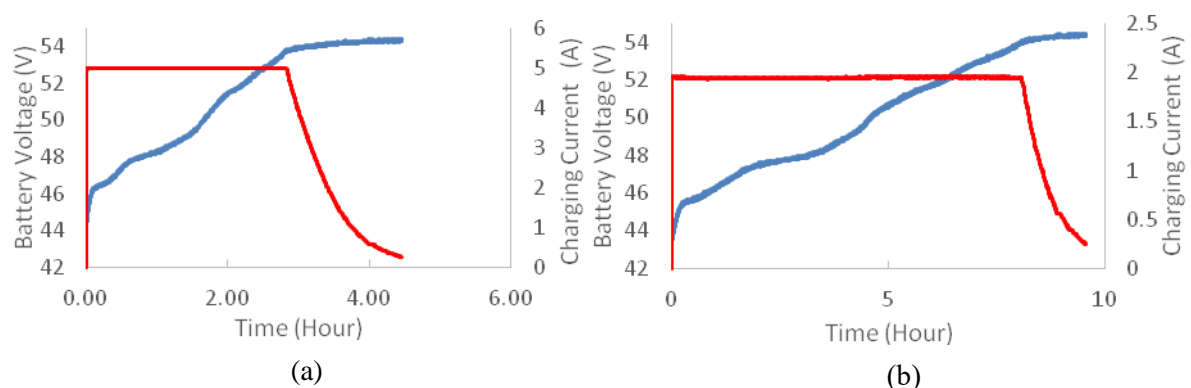


Figure 4. (a) Constant current charging 2 Ampere Graph (b) Charging Chart of 5 Ampere Constant Current

4.2. Discharging Battery Test with Constant Load

In the constant load discharging test 3 types of experiments were carried out, namely discharging with a constant load of $4\ \Omega$, $7\ \Omega$ and $19\ \Omega$. This test aims to look at the discharge characteristics of the battery to the large discharge currents that vary by varying the amount of load resistance. The greater the small value of the load resistance, the current that passes through the load will be even greater. Conversely, the greater the load resistance value, the greater the value of the current flowing. The selection of the test load resistance value considers the ability of the load to be flowed by current and the difference in discharge flow for testing one with other tests. Graphs of battery discharge characteristics can be seen in Figure 5.

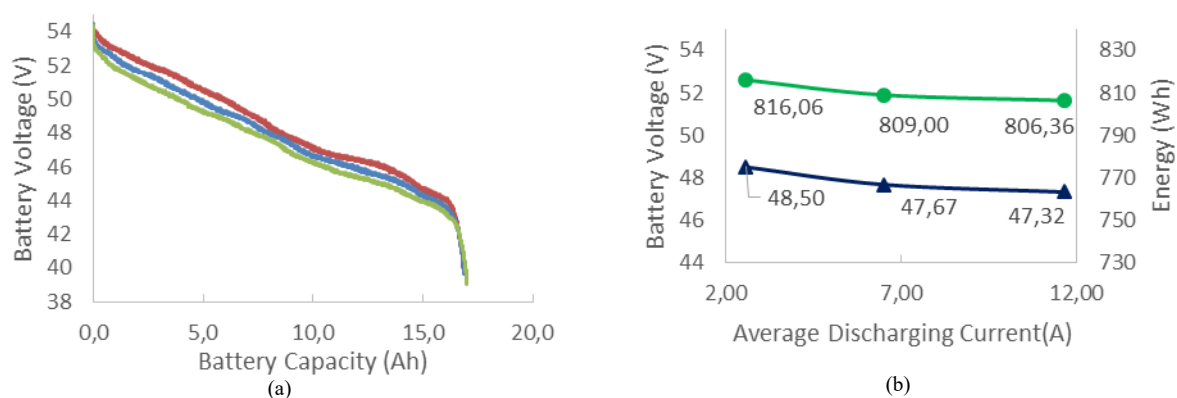


Figure 5. (a) Graph of Battery Discharge Characteristics (b) Relationship Graph of Average Battery Voltage, Average Discharging Current and Discharging Current Energy

From the graph above it can be seen that the value of the voltage decrease when connected to the load is greater if the value of the load gets smaller or the average current gets bigger. The average voltage value also decreases along with the decrease in the load value or the increase in the value of the average discharge current. The capacity that can be used is relatively the same for all three types of tests that range around 17 Ah. The average voltage value which decreases with a relatively large battery capacity causes the value of energy capacity that can be used also decreases. In other words, the greater the discharge flow, the smaller the energy capacity that can be used. The relationship between the battery's average voltage, average discharge current and battery energy capacity can be seen in Figure 5.

In terms of time it can be observed that the greater the load resistance value, the longer the battery discharge time. This is due to a smaller average current discharge value for greater load resistance so that the discharge time is longer. From Figure 6 can be seen the relationship of emptying time to the load resistance.

4.3. Analysis of Regenerative Braking Conversion Ability to Battery Voltage

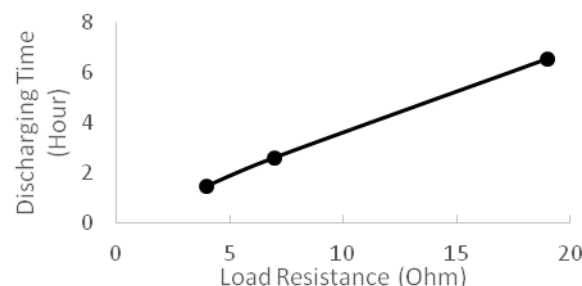


Figure 6. Graph of the Relationship of Emptying Time to The Load Resistance

Regenerative braking testing has succeeded in obtaining data showing that there is a conversion of mechanical energy into electricity. Then the researchers tested whether there was a change in battery capacity shown by measuring battery voltage before and after regenerative braking.

4.3.1. Zero Load

Zero load testing has a shorter regenerative braking time compared to full load testing. But the total power produced is less. Therefore the increase in battery capacity when compared to the initial conditions is not so significant.

Table 5. Battery Condition Before and After Regenerative Braking Zero Load

	Voltage)	Current (Ampere)	Power (KW)
Before	53,96	1.6	0.08633
After	54,18	-1,251	-0,0678

$$\Delta V_{\%} = \frac{V_{after} - V_{before}}{V_{before}} \times 100\% \quad (8)$$

$$\Delta V_{\%} = \frac{54,18 - 53,96}{53,96} \times 100\% = 0.407\% \quad (9)$$

Based on calculations using equations 9, the value of the increase in battery voltage is 0.407%.

4.3.2. Full Load

Full load testing has a longer regenerative braking time which is about 21 seconds. This happens because it requires a greater power in total to stop vehicles with a much larger mass load. In accordance with Newton's legal principles, objects with greater mass require greater force to change their initial conditions. Furthermore, if the total force to stop the vehicle multiplied by the distance of the vehicle for 21 seconds it will produce a greater energy value. Furthermore, if converted into electric energy produces a greater value of increased battery voltage capacity.

The presence of back current shows the battery charging process. The power produced during the regenerative braking process is the result of multiplication between the current and voltage values.

Table 6. Battery Conditions Before and After Regenerative Braking Full Load

	Voltage)	Current (Ampere)	Power (kiloWatt)
Before	47.63	33.91	1,61521
After	50.47	-0.107	-0,00538

$$\Delta V_{\%} = \frac{50,47 - 47,63}{47,63} \times 100\% = 5,96\% \quad (10)$$

Based on the calculation, the value of the addition of a battery voltage of 5.96 % was obtained

5. Conclusion

From the results of the tests carried out, some conclusions can be drawn which include KARLING battery charging characteristics, the battery voltage rises linearly when the current conditions are constant while the charging current drops exponentially when the voltage is constant. Furthermore, the greater the charging current, the smaller the energy efficiency. When charging with a constant current of 2 Ampere the energy efficiency is 96.88% while charging with a constant current of 5 Ampere the energy efficiency is 95.51%. The conditions that make it possible to charge KARLING batteries quickly (fast charging) is that the charging current is 30.27 Ampere for a charging time of 60 minutes. When discharging, the lithium-ion KARLING battery voltage drops linearly until it approaches the battery's cutoff voltage then drops drastically until the BMS disconnects the circuit. The greater the load resistance, the longer the discharge time. 4 Ohm loads require a discharging time of 1.46 hours, 7

Ohm load requires a 2.6 hour discharge time and 19 Ohm load requires a discharge time of 6.54 hours. The greater the load resistance, the greater the energy capacity of the battery that can be used. 4 Ohm load uses 806.36 Wh energy, 7 Ohm load uses 809 Wh energy, and 19 Ohm uses 816.06 Wh energy. The value of the battery voltage capacity increasing during testing without load is 0.407% and the value of adding battery voltage during full load testing is 5.96 % while regenerative braking occurred.

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