Analysis of the Effect of the Motor Temperature to Brushless Direct Current Motor Performance on KARLING Electric Vehicle

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Abstract. Indonesia is a country that has tropical climate with average temperature vary in between 27°C until 37°C. BLDC motor industry is not common in Indonesia so that has to be imported from another country mostly subtropical countries. BLDC motor is built according to subtropical characteristics. Therefore, BLDC motor performance is changing in Indonesia due to the temperature differences. The following methods are used in the study: laboratory experiment and field test using electrical vehicle. The temperature in laboratory is in range between 23°C up to 55°C. However the field temperature varies from 27.7°C and 34.2°C. The increasing temperature inside the motor in laboratory and field experiments conducts modification of BLDC motor parameters. The rising motor temperature degrades the current and torque of motor, but increasing the rotation velocity of the motor.

1. Introduction
BLDC (Brushless Direct Current) motor is an electric engine that converts electrical energy into mechanical energy. Today the use of BLDC motors has been widely applied to various fields, such as electric vehicles, industry, and housing. The use of BLDC motor is due to their characteristics that are easily controlled, high speed, little noise, and high durability. To support the performance of the BLDC motor, several observations are needed on the motor parameters including magnetic field density, voltage, EMF back voltage, current, rotor speed, torque, and efficiency of the motor. BLDC motor parameters can be affected by factors originating from the environment and surrounding conditions, thus affecting the characteristics of the motor.

The data shows that the country of Indonesia is a country that is passed by the equator, this is evident from the astronomical location of Indonesia which is at 6 ° NL - 11 ° SL and 95 ° EL - 141 ° EL. Furthermore, Indonesia is also a country that has a tropical climate. It shows that Indonesia is a country with high solar radiation, and temperature of the region could reach 27-37 ° C. These Indonesian temperatures will affect the performance of BLDC motor.

Electric vehicles that will be developed in Indonesia need special attention to the problem of tropical temperatures. Most electric vehicles use BLDC motor as the main driving source. Electric vehicles are dynamic objects and are a necessity in the field of transportation. To save energy, the BLDC motor used in electric vehicles must work optimally. Therefore, it is necessary to study the influence of temperature on the performance of BLDC motor. So that the utilization of BLDC motor in various fields can work optimally with high efficiency.
2. **Brushless Direct Current Motors and The Effect Of Heat On Motor**

2.1. **Understanding Motor Brushless Direct Current**

*Brushless Direct Current Motor* (BLDC motor) is a synchronous motor with a permanent magnet that uses *Direct Current* power sources that are integrated with the inverter power supply and position sensors to control it [1]. These motors use three-phase current, but BLDC motor is not included in *Alternating Current* motor for the BLDC motor current sources from a single *Direct Current* source that is converted into *Alternating Current* voltage using 3-phase inverter. Electric motors work based on electromagnetic field principles.

2.2. **Brushless Direct Current Motor Construction**

In general, BLDC motors consist of three parts, namely the rotor, stator, and *Shaft*. The rotor is part of the motor that moves, the stator is the stationary part of the motor, and the *shaft* is coupled directly to the rotor. To determine the exact commutation timing of this motor so that a constant torque and speed is obtained, 3 hall and / or encoder sensors are needed [1].

2.3. **Change of BLDC Motor Parameter Due to Temperature**

2.3.1. **Temperature effect on coil resistance**

Motor coil resistance is a part that can cause heat in the motor. The material used in the motor coil determines the amount of resistance and resistance to heat. The temperature increase will cause an increase in resistance according to the conductor used.

| TABLE 1. Temperature coefficient of metals |
|--------------------------------------------|
| Conductor Material                        |
| Gold                                       | 0.0037 / °C |
| Silver                                     | 0.0038 / °C |
| Copper                                     | 0.0040 / °C |
| Aluminum                                   | 0.0043 / °C |

Here is the relationship equation of temperature rise with coil resistance [2].

\[
R_{\text{ending}} = R_{\text{beginning}} \times \left[1 + \alpha_{\text{conductor}} \times (T_{\text{ending}} - T_{\text{beginning}}) \right] \tag{1}
\]

2.4. **Temperature effects on magnetic fluxes**

Motor torque constants and voltage constants are related to magnetic flux density. Changes in magnetic flux to temperature increases depend on the magnetic material used.

| TABLE 2. Permanent Magnet Material Temperature Coefficients |
|-----------------------------------------------------------|
| Magnet Material                                           | Maximum Temperature |
| Cobalt Nickel Aluminum                                    | -0.0002 / °C, 540 °C |
| Samarium Cobalt                                           | -0.0004 / °C, 300 °C |
| Neodium Iron Boron                                        | -0.0012 / °C, 150 °C |
| Ceramics                                                  | -0.0020 / °C, 300 °C |
Here is the temperature relationship equation with constant torsion and voltage constants.

\[ K_{\text{ending}} = K_{\text{beginning}} \times \left[ 1 + \beta_{\text{magnet}} \times (T_{\text{ending}} - T_{\text{beginning}}) \right] \]  

(2)

Motor torque is directly related to motor coil resistance and torque constants. The coil resistance has an effect on the amount of current flowing in the coil.

\[ I_r = \frac{v_r}{R_{\text{ending}}} \]  

(3)

\[ T_r = I_r \times K_t \]  

(4)

3. Research Methodology the Effect of Motor Temperature On BLDC Motor Performance

3.1. Design of BLDC Test-Rig Motor

The vehicle made is not a vehicle used in traffic conditions normally but a vehicle designed for research and development. Test-rig is a device used to test mechanical and electrical equipment. Test-rig is made of holo-square iron material with a thickness of 3mm and a length of 6m. Iron material is used because of the material properties that are suitable for testing needs. The nature of the points of elasticity, stress, and strain of iron material in accordance with the needs of the load to be given to the test-rig.

3.2. Designing Ultra-Compact Eco-friendly Vehicles

Ultra-Compact Eco-Friendly Vehicle (KARLING) are environmentally friendly vehicles that use electric motors as the main drivers. The electric motor used is a BLDC (Brushless Direct Current) motor which is supplied by a lithium-ion battery and uses a controller that has an inverter in it. This vehicle is designed and made to be a renewable energy powered vehicle solution with the concept of urban city car. KARLING is made to meet the capacity of 2 people.

| Table 3. KARLING specifications |
|------------------|--------|
| \( C_{gr} \)     | 0.02   |
| \( m \)         | 280 kg |
| \( g \)         | 9.84 m/s² |
| \( \rho \)      | 1.18 kg/m³ |
| \( C_{gu} \)    | 0.38   |
| \( A \)         | 1.18 m³ |

The force applied to the car include the frictional force of wheels, air friction force, the force of acceleration, and gravity. With the design constants of karling the total force can be written and calculated through the following equation,

\[ F_{\text{total}} = F_{\text{wheels friction}} + F_{\text{air friction}} + F_{\text{acceleration}} + F_g \]  

(5)

\[ F_{\text{total}} = C_{gr} N \cos \theta + \frac{1}{2} \rho v^2 C_{gu} A + ma + mg \sin \theta \]  

(6)
To calculate the total torque from KARLING can use the equation,

\[ \tau_{\text{wheel}} = F_{\text{total}} \times r \]  

(7)

Figure 1. Design Research Part (a) Test-rig design. (b) KARLING’s design on Autodesk Inventor

3.3. KARLING Electrical Design

The BLDC motor used is 1000W 205 40H BL1 BLDC Electric Bike Bicycle Spoke Motor Hub produced by QS MOTOR. 1000W 205 40H BL1 BLDC Electric Bike Bicycle Spoke Hub is used to be able to support car loads and could reach a maximum speed of 50 km/h. The controller used is the KBL48151X product from Kelly Controller. The controller can support 24 - 48V voltage sources with a maximum current of 150A and is used to control BLDC motors. The battery used has a voltage equal to the voltage to drive the motor and a capacity of 20Ah. The battery circuit is designed using batteries with lithium-ion type.

3.4. BLDC Motor Performance Data Collection Method

- Motor Testing at the Laboratory
  Testing of BLDC motor performance was tested in the laboratory using test-rig.
- Motor Testing on KARLING
  Testing the BLDC motor performance on KARLING is done with a flat road scenario. Tests were carried out on the campus of the University of Indonesia.

3.5. Motor Parameter Retrieval

BLDC motor engines parameter are voltage constants, torque constants, and motor resistance. The following is the result of the calculation of the motor engine parameters.

| Voltage of 0.8 (V) | Total Voltage (V) | Voltage Motor (V) | Motor Current (A) | Line-line resistance (Ohm) |
|-------------------|------------------|-------------------|------------------|--------------------------|
| 0.272             | 0.389            | 0.117             | 0.5              | 0.234                    |
| 0.321             | 0.464            | 0.143             | 0.6              | 0.238                    |
| 0.363             | 0.523            | 0.16              | 0.7              | 0.229                    |
| 0.425             | 0.604            | 0.179             | 0.8              | 0.224                    |
| 0.483             | 0.699            | 0.216             | 0.9              | 0.240                    |
| **Average**       |                  |                   |                  | **0.233**                |
Table 5. Electric Motor Constants Calculations

| Rotator rotation (rad / s) | Back Voltage EMF (V) | Line | Phase |
|---------------------------|----------------------|------|-------|
| 18.39                     | 10.37                | 0.56 | 0.33  |
| 19.59                     | 11.24                | 0.57 | 0.33  |
| 20.06                     | 11.57,6              | 0.58 | 0.33  |
| 18.37                     | 10.41                | 0.57 | 0.33  |

Average 0.57 0.33

4. Analysis Of Data Effect Of Motor Temperature On Bldc Motor Performance

4.1. Laboratory Testing Data Analysis

The study of BLDC motor performance on the temperature in the laboratory was tested at ambient temperature of 23°C and ambient temperature of 55°C. Testing the performance of a BLDC motor with a load of 2.84 kg is done with 2 different motor temperature conditions. With an ambient temperature of 23°C, motor temperature after the run was recorded at 31.4°C. At ambient temperatures of 55°C, motor temperature after the run was recorded at 60.4°C.

Table 6. Main Data Of 2.84 Kg Load Testing

| Current Controller (A) | Peak Value | Constant Value | Change Value |
|------------------------|------------|----------------|--------------|
| 31.4°C                 | 7.48       | 4.86           | 1.53         |
| 60.4°C                 | 5.95       | 3.53           | 1.33         |

| Phase Flow (A)         | 10.31      | 4.18           | 1.04         |
| 9.27                   | 3.85       | 0.33           |

| Motor Speed (rpm) Motor | 570.2      | 569.6          | 8.4          |
| 578.6                  | 576.7      | 7.1            |

| Torque (Nm)            | 5.89       | 2.39           | 0.79         |
| 5.10                   | 2.12       | 0.27           |

To clearly see the changes in motor parameters to temperature can be seen using a graph consisting of the controller current graph, phase current, motor speed, and torque.

Figure 2. Laboratory Data Analysis: (a) Controller Current Graph Changes (b) Motor Phase Current Graph Changes
At the start of the motor rotating, requires a larger force due to driving the motor from resting with high inertia. At the beginning of the motor rotating, the controller current loads 2.84 kg with a motor temperature of 31.4 °C valued at 7.48 A higher than the current with a motor temperature of 60.4 °C which is worth 5.95 A. The average current of the controller steady state temperature of 31.4 °C 4.86 A, greater than the temperature of 60.4 °C the average current is 3.53 A. At a motor temperature of 31.4 °C the initial state of the motor rotates, the phase current is 10.31 A. While the motor temperature is 60.4 °C the initial state of the motor rotates, the phase current 9.27 A. The phase current has decreased due to the increase in motor temperature.

The controller current loads of 2.84 kg with motor temperature of 31.4 °C in second of 2 to second 50 is experiencing a decrease. The decrease is due to the increase of motor rotation speed, the required torque drops. The current controller loads 2.84 kg with a motor temperature of 60.4 °C in second 2 to second 50, an insignificant increase occurs. The motor rotates in second 2 to second 50, the three motor phase current at a motor temperature of 31.4 °C are greater than the three motor current phase of motor temperature of 60.4 °C. This is caused by the increase in motor impedance to the increase in motor temperature.

The motor rotation speed with 2.84 kg load at a motor temperature of 31.4 °C lower than the motor speed of the motor with 60.4 °C temperature. In second 1 to second 50, each measurement point the motor rotation speed is higher due to the increase in motor temperature. The average motor rotation speed at a temperature of 31.4 °C is 569.7 rpm, and the average temperature of 60.4 °C is 576.7 rpm. This indicates that the increase in motor temperature causes the motor rotation speed of 2.84 kg load has increased by 7.1 rpm. Temperature rise causes a decrease in magnetic field density. The magnetic field density decrease results in a decrease in the magnetic field flux. Before comparing the motor torque of 2.84 kg load at different temperature conditions, first calculate the torque constant that changes due to the increase in temperature using (equation 7). In (Figure 3) it is explained that there is a difference in motor torque at a motor temperature of 31.4 °C with torque at a temperature of 60.4 °C. It is noted that the torque at second 1 the motor temperature is 31.4 °C at 5.89 Nm and at temperature 60.4 °C motor is 5.10 Nm. The temperature increase decreases the initial motor torque with a decrease of 0.79 Nm . At second 2 to second 50, the average motor torque at a motor temperature of 31.4 °C is 2.39 Nm and at a motor temperature of 60.4 °C the average motor torque is 2.12 Nm. Torque reduction in the initial state and second 2 to second 50 due to the increase in motor temperature. Motor phase current and motor torque constants decrease due to the increase in motor temperature.

4.2. Data Analysis on KARLING
Tests on KARLING are carried out at the University of Indonesia environment, testing scenarios are carried out on horizontal roads. Vehicle testing is carried out in the morning and evening conditions, so testing occurs in 2 different motor temperature conditions. Morning testing was carried out at 10:03:37 WIB, while in the afternoon it was held at 16:32:00 WIB. In the morning test the ambient temperature was 27.7 °C and the motor temperature was recorded at 32.8 °C. On the afternoon test the ambient temperature was 34.2 °C and the motor temperature was recorded at 37.8 °C. Here is the data set important testing of the motor on the KARLING that will be used when analyzing it.
Table 7. Experiment results

|                      | Reach Constant Speed | Constant speed | Change Value |
|----------------------|----------------------|----------------|--------------|
|                      | 32.8 °C               | 37.8 °C        |              |
| Current Controller (A) | 18.15               | 15.93          | 2.22         |
|                      | 32.8 °C               | 37.8 °C        |              |
|                      | 26.74               | 28.57          | 1.83         |
| Phase Flow (A)       | 40.97               | 38.44          | 2.53         |
| Rotational Speed (rpm)| 225.03             | 240.72         | 10.51        |
| Motor Torque (Nm)    | 25.51               | 21.56          | 1.59         |

Figure 3. Vehicle Data Analysis: (a) Controller Current Changes on KARLING (b) Phase Current Changes on KARLING

The vehicle at a motor temperature of 32.8 °C requires 23 seconds to reach a constant speed. The vehicle at a motor temperature of 37.8 °C requires 28 seconds to reach a constant speed. Temperature peak current 32.8 °C was recorded 36.11 A, is greater than the peak current temperature of 37.8 °C, which is only 36.09 A. The temperature rise causes a decrease in the controller current when it reaches a constant speed.

At constant speed, the controller current at a motor temperature of 32.8 °C is 26.7 A lower than the current at a temperature of 37.8 °C at 28.6 A. Because at a temperature of 37.8 °C, larger torque is needed to maintain the constant speed, so more current is required. In second 1 to second 23 is a condition where the vehicle reaches a constant speed. Under these conditions, a 3-phase motor current at a motor temperature of 32.8 °C is higher than the temperature phase current of 37.8 °C.

The temperature rise results in a decrease in the motor phase current when the vehicle conditions remain stationary until they reach a constant speed. When the condition of the vehicle is running at a constant speed, the motor phase current at a temperature of 32.8 °C is lower than the motor phase current temperature of 37.8 °C. The increase in temperature causes an increase in the motor phase current when the vehicle is at constant speed. This is because at a temperature of 32.8 °C less torque is required to drive KARLING than the torque required at a temperature of 37.8 °C.
When the vehicle is from stationary to a constant speed that is in sample 1 to sample 2 there is a change in motor speed at 2 different motor temperatures. KARLING motor rotation speed at motor temperature 32.8 °C with an average value of 225 rpm is lower than the motor rotation speed at a temperature of 37.8 °C with an average value of 240.7 rpm. The increase in motor temperature causes the motor rotation speed to increase when KARLING reaches a constant speed. This is because the magnetic field density decreases in the event of an increase in temperature. The magnetic field flux decreases with decreasing density of the magnetic field. Decreased magnetic flux causes an increase in motor rotation speed.

When the KARLING speed is constant, the change in motor rotation speed is different from testing in the laboratory. Under conditions of constant speed, the motor rotation speed at motor temperature is 32.8 °C is higher with an average value of 326.4 rpm from a motor speed of motor temperature 37.8 °C with an average value of 315.9. This is because at a temperature of 32.8 °C the torque needed for a vehicle to move constantly is enough so that torque decreases. Both tests at different motor temperatures, each condition of the motor temperature, the torque constant changes. Changes in the torque constant of motor temperature 32.8 °C. At the time vehicle is on stationary condition until a constant speed which is on the second 1 until the second 23 motor torque at a motor temperature of 32.8 °C is higher with an average of 23.15 Nm of torque compared with the motor torque at a motor temperature of 34.2 °C with an average torque of 21.56 Nm.

The increase in motor temperature causes the motor torque at KARLING to decrease. This is because the magnetic field density decreases with temperature rise. This decreasing magnetic field density causes the torque constant to decrease. When KARLING is at a constant speed, the motor torque with a motor temperature of 32.8 °C with an average torque of 18.20 Nm is lower than the motor torque of motor temperature of 37.8 °C with an average torque of 20.66 Nm. At a constant speed with a temperature of 32.8 °C, the torque needed to maintain a constant speed is sufficient so that torque decreases.

5. Conclusion
We can conclude from the experiment that the increase in motor temperature in the motor test in the laboratory with 2.84 kg load resulted in a decrease in the current controller, motor phase current, and motor torque. Moreover, the increase in motor temperature in the motor test in the laboratory with 2.84 kg load resulted in an increase in motor rotation speed. When the vehicle is stationary until it reaches a constant speed, the controller current, the motor phase current, and the motor torque decrease with temperature. Whereas in a vehicle with a constant speed of the controller, the motor phase current, motor torque increases with temperature rise. The ambient temperature rise results in an increase in motor rotation speed when KARLING reaches a constant speed. While at KARLING with a constant speed, the increase in temperature causes a decrease in the motor's rotational speed.

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References

[1]. Putra, Julianto. Design of Environmental Conscious Vehicle (KARLING) as an Environmentally Friendly Vehicle Solution. 2016. Depok: University of Indonesia.

[2] Carmen Lungoci, and Stoia. 2008. Temperature Effects on Torque Production and Efficiency of Motor with NdFeB. Brasov: University of Brasov.

[3] Buchi, Roland. Brushless Motor and Controller. 2012. Norderstedt: Books on Demand GmbH. I. Dudzikowski; S. Kubzdela, Thermal Problems in Permanent Magnet Commutative Motors. 1997. Poland.

[4] Chapman, Stephen J. Electric Machinery Fundamentals Fourth Edition. 2005. New York: The McGraw-Hill.

[5] Cassat Alain, Espanet Christophe, Wavre Nicolas. BLDC Motor Stator and Rotor Iron Losses and Thermal Behavior Based on Lumped Schemes and 3-D FEM Analysis. 2002. United State.

[6] Yutian Wang, Haoyu Li, Decheng Ren. Characteristics of BLDC Motor Drive System at High Temperature. 2016. China: Harbin Institute of Technology.

[7] T. Kenjo, S. Nagamori. Permanent-Magnet and Brushless DC Motor. 1985. United State: Oxford University.

[8] Febri Arwan N, Agus P, Yanuarsyah H, Nana H. 2012. The Calculation of Electrical Motor and Lithium Battery Capacity on the Horizon of ITB Electric Car. School of Electrical Engineering and Informatics, Bandung Institute of Technology, Indonesia.