Analysis of The Influence of Loading Variations Toward Brushless Direct Current Motor Performance on KARLING Electric Vehicle

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Abstract. One type of electrical motors often used for electric vehicle purposes is Brushless Direct Current Motor (BLDC Motor). BLDC motor performance can be seen from its current line, electromagnetic torque, rotational speed, induction voltage, and input power as the parameters. The research’s aim is to find out the effect of loading towards BLDC motor performance on the electric vehicle. The loading variations are used in the form of passenger weight and track characteristics variations. The variation of passengers’ weight is 55 kg, 78 kg, and 143 kg. In this study obtained line current value when the passengers load 143 kg is 41.52 A. Furthermore, the values of the electromagnetic torque and energy consumption in the same weight are 23.88 Nm and 0.06 kWh/km. To ascertain the effect of track characteristics variations to the motor parameter, variations of track characteristics are done in trajectory 0° and 1.25°. The outcome is the 1.25° tilted track has higher energy consumption but lower speed.

1. Preliminary
Based on Ministry of Environment from the inventory of emissions result which held in Indonesia, exactly in Palembang and Surakarta on 2010, transportation sector is an important source of contaminants towards air and greenhouse gases in the city. The data shows that contribution of fine particles emission and greenhouse gases emission from transportation sector is in range 50% up to 70% and 23% respectively [1]. One attempt to address the problems is using electrical energy based transportation technology.

One kind of electric motor that commonly used as electric vehicle propulsion is brushless direct current (BLDC) motor. The usage of BLDC in electric vehicle must concern about the characteristics from its working parameters such as electric current, torque, and speed that affected by the condition of loading. Nevertheless, the condition of loading BLDC motor weighs the rate of electric energy consumption also.
2. General Definitions of Brushless Direct Current (BLDC) Motor

2.1. Brushless Direct Current (BLDC) Motor
BLDC motor is direct current electric motor which used permanent magnet and brushless commutated. Flemming’s left hand rule explains Lorentz’s Force meanwhile induction voltage (back electromotive force) is interpreted by Flemming’s right hand rule.

2.2. Flemming’s Hand Rule
Flemming’s hand rule explains Lorentz’s Force and induction voltage (back electromotive force). Left hand rule explains Lorentz’s Force meanwhile induction voltage (back electromotive force) is interpreted by right hand rule [4].

\[ \vec{F} = \vec{i} \times \vec{B}l \]  
\[ \vec{e} = \vec{v} \times \vec{B}l \]

with,
- \( \vec{F} \) = Force (Newton)
- \( \vec{e} \) = Induction voltage (Volt)
- \( \vec{B} \) = Magnetic Field (Tesla)
- \( \vec{l} \) = the length of conductor (meter)
- \( \vec{i} \) = Electric current (Ampere)
- \( \vec{v} \) = speed (meter per second)
- \( l \) = the length of conductor (meter)

2.3. The Position and Speed of Mechanic and Electric
Back electromotive force or back e.m.f is generated from rotational motion of permanent magnet so there is a change of flux number per time unit. Here is the equation [5]:

\[ \theta_e = \frac{Nm}{2} \theta_m \]  
\[ \omega_e = \frac{Nm}{2} \omega_m \]

with,
- \( \theta_e \) = electric position
- \( \theta_m \) = mechanic position
- \( N_m \) = magnetic poles

2.4. Back Electromotive Force Voltage
Back electromotive force or back e.m.f is generated from rotational motion of permanent magnet so there is a change of flux number per time unit. Here is the equation [5]:

\[ e_b = \frac{d \delta}{dt} = \frac{\delta e}{dt} \]  
\[ \Phi g = B_s A_s = \frac{2\pi}{Nm} B_s L_{st} R_{ro} \]  
\[ |e_b| = E_b = 2N_m N B_s L_{st} R_{ro} \omega_m \]

with,
- \( E_b \) = Induction Voltage (Volt)
- \( L_{st} \) = the length of axial motor (meter)
- \( R_{ro} \) = the length of outer radius of rotor (meter)
2.5. Electromagnetic Torque
Torque is a number of force which can make a thing done some rotational motion.

\[ [T] = \frac{E_b i}{\omega m} = 2N_m N B_s L_s R_{co} i = K_i i \]  

(8)

with,
\( K_i = \) constant of torque (Nm per Ampere)
\( \lambda = \) scaling flux (Weber)

2.6. Power
Power is number of energy per time. Electric power is supplied as input power to motor from the battery. Here is the equation,

\[ P_{in} = V I \]  

(9)

3. The Design of KARLING

3.1. Determination of Motor Specification Needed
BLDC motor specification determination done by mathematics calculation of torque value, rotational speed, and power needed. Force applied on a vehicle mathematically written on these equation [6].

\[ F_{tot}(v) = C_{rr} N\cos\theta + \frac{1}{2} \rho v^2 C_d A + m \frac{dv}{dt} + mg \sin\theta \]  

(10)

with,
\( C_{rr} = \) Friction Coefficient of wheel
\( C_d = \) Friction Coefficient of air

The value of parameters to design KARLING is written on the Table 1.

| Table 1. Value of KARLING Design Parameters |
|---------------------------------------------|
| Parameters       | Value        |
|------------------|--------------|
| \( C_{rr} \)     | 0.02         |
| \( M \)          | 280 kg       |
| \( g \)          | 9,84 m/s²    |
| \( \rho \)       | 1,18 kg/m³   |
| \( A \)          | 1,18 m²      |
| \( C_d \)        | 0.38         |

With targeted speed constantly on 25 km/hr or 8.3 m/s with trajectory 5% or 2.5o, so:

\[ \tau_{motor} = 61,84 \text{ Nm} \]
\[ \omega_{motor} = 25,32 \text{ rad/s} \]
\[ P = \tau_{motor} \times \omega_{motor} = 1565,02 \text{ Watt} \]

Then to get targeted speed constantly on 40 km/hr or 11.11 m/s on non-trajectory road as followed:

\[ \tau_{motor} = 28,87 \text{ Nm} \]
\[ \omega_{motor} = 40,53 \text{ rad/s} \]
\[ P = \tau_{motor} \times \omega_{motor} = 1170,1 \text{ Watt} \]
3.2. Measurement of Machine Constant

Based on Table 2 we can conclude that the value of torque constant in this study is 0.57 Nm/A within induction voltage of line from BLDC motor used is 0.57 V.s/rad.

### Table 2. BACK E.M.F Constant

| Rotational Speed (rad/s) | Induction Voltage (V) | $K_{e-line}$ (Vs/rad) |
|-------------------------|-----------------------|------------------------|
| 18.39                   | 10.77                 | 0.59                   |
| 19.6                    | 11.24                 | 0.57                   |
| 20.01                   | 11.55                 | 0.57                   |
| 19.76                   | 11.23                 | 0.57                   |
| 19.59                   | 11.03                 | 0.56                   |
| **Average**             |                       | **0.57**               |

Furthermore, vehicle’s electric system, which is integrated system between driver element, energy storage element, and controlling element, is designed. Driver element used is electric motor. Moreover, energy storage element used is battery Li-Ion. Then, controlling element meant is electric motor controller.

### Table 3. BLDC Motor Specification

| Brand       | QS Motor            |
|-------------|---------------------|
| Type        | Outer Rotor         |
| Power       | 1000 W – 2000 W (2000 W for a minute) |
| Rated Voltage | 48 V – 96 V         |
| Max. Phase Current Recommended | 89-112 A |
| Continuous battery current | 20.8 A |
| Maximum battery current | 41.5 A |
| Angular velocity | 583 rpm (no load) |

After that, the battery pack designed has adjusted specification with specification of BLDC motor and the aging duration as followed:

### Table 4. Battery Pack Specification

| Series × paralel | 13S × 8P |
|------------------|----------|
| Maximum discharging current | 160 A |
| Rated capacity   | 20 Ah    |
| Rated voltage    | 48 V     |
| Final discharge voltage | 39 V |
| Charging voltage | 54 V     |
| Standard charging voltage | 2 Ampere |
Then, BLDC motor controller used is Kelly Controller type KB48151X with these specifications:

| Table 5. BLDC Motor Controller |
|--------------------------------|
| **Brand** | Kelly Controller |
| **Type** | KBL48151X |
| **Controller voltage supply** | 18 V – 90 V |
| **Battery voltage** | 18 V – 1.25 x Nominal Voltage |
| **Motor current limit (1 min)** | 100 A – 500 A |
| **Continuous motor current limit** | 60 – 200 A |

4. Testing and Analysis Result

The experiments are done not only by riding with passenger’s weight variations as 55kg, 78kg, and 143kg on flat road, but also trajectory road of 1.25o with passenger’s weight is 55kg. The parameters of observation are line current, electromagnetic torque, rotational speed, induction voltage, and energy consumed.

4.1. Characteristics of Current Line & Electromagnetic Torque

Figure 2 tell us about current line waves on BLDC motor when KARLING moves with passenger’s weight 55kg, 78kg, and 143kg on flat road.

![Figure 2](image)

*Figure 2. Effect of load variations toward: (a) Line current characteristic (b) Electromagnetic torque characteristic*

Current value fluctuated in the beginning since the rotational speed of motor still low therefore current flow fluctuation based on rotor position is barely read by Hall Sensors. Then, there are phases where current line value and electromagnetic torque are quite stable in the range of 43 A – 49 A and 25 Nm – 27 Nm respectively. However there is a gap in duration when current line value relatively stable. The experiment using passenger’s weight 55kg ends in 28 seconds. After that, experiment with load of 78 kg and 143 kg end within 33 seconds and 41 seconds respectively. On the stable condition, higher load make the time duration longer. It is because current value is quite as same so that electromagnetic torque of motor also, while passenger’s load of the vehicle is different. As the result, acceleration of vehicle with lighter load will be higher than the heavier load to reach constant rotational speed.
As seen on the Table 6, we can conclude that the passenger’s load has positive correlation with the current line and the electromagnetic torque. The next phase shows fluctuation of electromagnetic torque despite it was relatively rising right before it lower again due to bumpiness of the road. So that, there is a higher friction toward vehicle, the controller will gain the current line to increase motor torque as aftermath.

### 4.2. Characteristics of Angular Velocity and BEMF Voltage

![Figure 3](image-url)

**Figure 3.** Effect of load variations toward: (a) Angular Velocity Characteristics (b) B.E.M.F. voltage characteristics

### Table 6. Experiment result

| Load (kg) | Time when Stable (s) | Average Current Line (A) | Average Electromagnetic Torque (Nm) |
|-----------|----------------------|--------------------------|-------------------------------------|
| 55 kg     | 37 – 43              | 30.08                    | 17.24                               |
| 78 kg     | 41 – 46              | 36.41                    | 20.87                               |
| 143 kg    | 47 – 55              | 41.66                    | 23.88                               |

### Table 7. Effects of load toward speed and induction voltage

| Load (kg) | Starting Time (s) | Speed (rad/s) | Induction Voltage (V) |
|-----------|-------------------|---------------|------------------------|
| 55        | 34                | 33            | 18.88                  |
| 78        | 37                | 34            | 19.7                   |
| 143       | 46                | 32            | 18.23                  |

Differences in values between variations appear insignificant and may be influenced by different ways of driving. There is a more significant difference over the duration of time required to achieve relatively constant conditions. Between testing with a passenger weight of 55 kg with 78 kg the difference in duration of 3 seconds. While between the test 55 kg with 143 kg difference is 13 seconds. This is because the difference between the weight of passengers between the test and passenger weight of 143 kg with 55 kg is much greater than between the test with the weight of passengers 78 kg with 55 kg. The greater the weight of the passenger of the vehicle the greater the duration of time required to achieve the condition of motor rotation speed is relatively constant even greater. This is because when the phase motor speed is not constant, large electromagnetic torque relatively the same but different vehicle passenger weight, resulting in differences in the acceleration of the motor.
4.3. Characteristics of Power Input and Energy Consumption

Based on Figure 4 below, it can be seen that the heavier the passenger of the vehicle in this test, the more changes the input power value and the duration of time required to reach the peak value. Consequently there is also a difference in the energy required to reach that peak point, which is 0.007 kWh when passenger weight is 55 kg, 0.0085 kWh when passenger weight is 78 kg, and 0.012 kWh when passenger weight is 143 kg. It can be seen that the greater the weight of the passengers, the greater the energy required.

![Figure 4. Input power characteristic](image)

Then the input power value decreases when the motor's rotational speed is relatively stable. In this phase, the motor input power value at the test with a passenger weight of 55 kg decreased to an average input power rating of 1202.07 W. Then on the test with a weight of 78 kg passengers decreased to an average input power value of 1391.11 W. Further on the test with the weight of passenger 143 kg down to the average input power value 1517.44 W. It can be seen that although the same phase of decline, there is an influence of the difference in weight of passenger vehicles. The greater the weight of passenger vehicles then the required motor input power value is also greater. Furthermore, in the test with a passenger weight of 55 kg, the total energy consumption is 0.0184 kWh or 0.046 kWh / km. Then on the test with a weight of 78 kg passengers, the total energy consumption is 0.0205 kWh or 0.051 kWh / km. Moreover, on testing with passenger weight of 143 kg, the total energy consumption is 0.0236 kWh or 0.059 kWh / km. Seen that the greater the weight of passengers on the vehicle the greater the energy consumption.

4.4. Effect of The Slope of The Track

On testing in flat trajectory, line current value of the average at this stage is 46.12 A While on the track testing at a large horizontal channel current value of the average in this phase was 45.81 A. In addition, the mean value of the electromagnetic torque the average in this phase is 26.44 Nm, whereas in the test on the horizontal trajectory the average electromagnetic torque value in this phase is 26.25 Nm. If based on the value it is seen that the difference in value that occurs is very small or insignificant. However, if the terms of the duration characteristic value changes seen a significant difference. This is because the force due to gravity on the horizontal trajectory is smaller than on the uphill track. Because the value of the electromagnetic torque is relatively similar but the force due to gravity working on the test on the trajectory is higher, the duration of this phase is greater on the uphill track test. It was also seen that the motor acceleration and induction voltage in the test with the uphill trajectory were lower than in the test with horizontal track contours. Energy consumption in testing on the uphill track is also larger than in the test on the horizontal track.
### Table 8. Effects of the slope of the track

| Parameter                                      | Track Character |
|------------------------------------------------|-----------------|
| Time duration of relatively stable current line (s) | Flat 28, 1.25° 40 |
| Time duration of relatively stable electromagnetic force (s) | Flat 28, 1.25° 40 |
| Rotational speed of motor on second of 39 (rad/s)    | Flat 33.11, 1.25° 24.91 |
| Induction voltage on second of 39 (V)                | Flat 19.98, 1.25° 14.28 |
| Energy consumption (kWh/km)                        | Flat 0.046, 1.25° 0.07 |

5. Conclusion

The results of these tests show that the greater the weight of the passengers and the contours of the uphill path leading to increased value of line current, electromagnetic torque, and energy consumption of the motor. Then also lead to a reduction of motor acceleration. In this study, the value of channel flow, electromagnetic torque, and the largest energy consumption when passenger weight of 143 kg, i.e. 41.52 A, 23.88 Nm, 0.06 kWh/km for horizontal trajectory. Moreover, on the test with a slope of the path of 1.25° with lower acceleration and greater energy consumption of 0.07 kWh/km compared to the horizontal trajectory with the same passenger weight of 0.046 kWh/km

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