Design of 6S8P axial flux permanent magnet brushless DC motor with double-sided rotor

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Abstract. Electric motors developed rapidly in this decade. That is because electric motors have many advantages over conventional engines. The types of electric motors also vary, from low rated power to high rated power. Electric motors become an essential part of many sectors, such as industry and transportation. Brushless Direct Current Motor (BLDC) is one of the electric motors that has been developed because it has advantages compared to BDC motors. Low-power BLDC motors are widely used in several fields, such as computer construction, robots, and aviation. Research on the form of BLDC motor construction needs to be done to find out the maximum performance of a BLDC motor. Testing of a small motor axial flux permanent magnet brushless direct current with the double-sided rotor (AFPM BLDC DR) was carried out to determine the values of rotational speed, torque, mechanical power, and efficiency. Based on the test, a maximum rotational speed of 2365 rpm, the torque of 0.055 Nm, and the effectiveness of 70.34% are obtained.

Keywords: Electric motor, axial flux permanent magnet motor, double-sided rotor motor

1. Introduction
The Brushless Direct Current (BLDC) motor is one of the engines that is being widely studied. This motorbike applied in various sectors, such as automotive, astronomy, medical, and industry. BLDC motors are commonly in the industrial area. It is due to a simple design and has a high ability to spin at fast speeds [1]. There are two types of BLDC motors, namely Permanent Magnet Synchronous Motor (PMSM) and PMBLDC [2]. There are two types of BLDC motors based on their construction, namely radial and axial forms. Previous studies have shown that axial-flux BLDC motors have higher torque than radial fluxes [3]. Besides, the BLDC motor in the radial flux form has a higher power loss than the axial-flux way [4]. Radial BLDC motors have higher efficiency when rotating speeds are also higher, but at maximum speeds, the ability decreases [5].

Previous research on slotted BLDC and slotless BLDC has been carried out. Based on these studies, it is known that slotted BLDC motors have slower speeds than slotless BLDC motors, but slotted BLDC motors have higher torque than slotless BLDC motors [6]. Slotless BLDC motors have an efficiency of around 85% at speeds of 200 rpm and torque, which tends to be constant from
initial starting to 200 rpm [7]. However, BLDC motors have disadvantages than DC motors, where BLDC motors have higher torque ripple, noise, and vibration than DC motors [8].

Permanent magnets used in BLDC motors affect the density of magnetic flux. The thickness of the permanent magnet is very influential on the performance of the BLDC motor. Based on these studies, it found that the thicker the permanent magnet used, the higher the value of the resulting magnetic flux density [9]. The continuous use of magnets on BLDC motors results in high flux density motors [10]. The number of magnets in one polish affects the cogging torque of the engine. One magnet on one polish has a lower cogging torque than the use of several magnets on one motor polish [11]. The use of permanent magnet material affects motor torque. Permanent magnets from NdFeB magnets are known to have an effect on higher torque than the use of ferrite magnets [12]. Cogging torque can be reduced by modifying the shape of the permanent magnet on the rotor. Circular permanent magnets can minimize cogging torque to 62.5% [13].

The 3 phase BLDC motor can work, one of which uses a hall effect sensor [14]. The ability of the Hall effect sensor is beneficial for working even if one of the hall effect sensors is damaged or not functioning [15]. Besides, BLDC motors for the 5kW rated power scale obtained high speed and torque, namely 5050 rpm and 9.5 Nm [16]. The power efficiency of BLDC motor changes when the speed also changes. If the rate is higher, the motor power efficiency will also be higher [17].

This study aims to improve performance on BLDC motors. By using the 3 phase 6 slots, the eight-pole method in dual rotor axial-flux construction using NdFeB permanent magnets, the performance of BLDC motors can be improved. Tests are conducted to determine the value of rotational speed, voltage between phases, driver frequency, and motor current. Based on these tests, it can be analyzed the calculation of the amount of torque, input power, mechanical power, and efficiency. Power analysis needs to be done a review of power loss and electromagnetic energy in the motor.

2. Materials and methods

Motor design and design need to be calculated according to the target to be achieved. The prototype is designed to be suitable for small motor applications of 12V / 18V / 24V DC voltage sources with optimum efficiency.

2.1 Motor design

The construction is designed consisting of 6 slots and eight poles. The slots are connected Y-connected for a 3-phase configuration of the motor driver output. The motor performance targets are designed: 2000 rpm motor rotational speed, mechanical motor power of 22.2 W, and motor current 1.5 A. The permanent magnet on the rotor used is NeFeB. Required design of motor specifications to achieve this value. It is assumed that the electromagnetic power value is the same as the mechanical power value as equation 1.

\[
P_{elm} \approx P_m
\]

That is because power losses are not yet known when the motor is formed.

Then the electromagnetic torque can be calculated \( T_d \) from the following equation 2.

\[
T_d = \frac{P_{elm}}{2\pi n_s}
\]

Angular synchronous speed can be calculated from the motor rotational speed \( n_r \), which is \( n_s = \left(\frac{2\pi}{60}\right) n_r \). The unit of angular synchronous speed is \( r / s \), and the motor rotational speed is in rpm. The magnetic flux calculated from the measured value of the magnetic flux density \( B \) and the surface area of the permanent magnet [18]. The amount of the magnetic flux \( \Phi_f \) can be determined from equation 3.
The permanent magnet used is the NdFeB type shaped like a disc measuring 15 mm in diameter and 2 mm thick. On one side of the rotor, there are eight polishes as equation 4.

\[
\Phi_f = B \cdot A_{\text{magnet}} \cdot \frac{8}{8}
\]  

(4)

Where \( A \) is the area of the permanent magnet used. Winding factor \((k_w)\) can be calculated from the equation 5 [19].

\[
k_w = k_d k_p.
\]

(5)

where \( k_d \) = the distribution factor and \( k_p \) = the pitch factor [19]. The distribution factor and pitch factor calculated from the following equation 6.

\[
k_d = \frac{\sin(\pi / (2m_1))}{q\sin(\pi / (2m_1q))}
\]

(6)

\( q \) is the number of slots per pole per phase calculated from the formula \( q = s / (2pm) \), and \( m \) is the number of stages [19]. The pitch factor value calculated using the following equation 7.

\[
k_p = \sin\left(\frac{\pi W_c}{2 \tau}\right)
\]

(7)

\( W_c \) is the coil span, and \( \tau \) is the pole pitch measured in the number of coil sides, which is \( s = s / (2p) \). Where is the number of slots, and \( 2p \) is the number of poles [19]. There is a formula for calculating electromagnetic torque based on magnetic flux, distribution factor, and pitch factor [18] as equation 8.

\[
T_d = \frac{2}{\pi} m_1 N_1 k_w \Phi_f I_a
\]

(8)

Based on these equations can be broken down into the following equation. The comparison is to find the number of turns is determined by equation 9.

\[
N_1 = \frac{T_d \pi}{2pm_1 k_w \Phi_f I_a}
\]

(9)

Based on the design calculations under equations (1) to (8), we can find out the number of turns per slot needed, which is 175.9 turns.

2.2 Testing Analysis Tests

The tests performed are inter-phase voltage, motor current, driver frequency, and motor rotational speed. Based on the results of these tests, test analyses have been done. The testing analysis is needed to determine the value of motor performance through calculations. The test analyses calculated are motor rotational speed, torque, mechanical power, and efficiency.

To ensure the motor speed is as it should be, it is necessary to pass an analysis of the calculation of motor speed through frequency. Motor rotational speed calculated through the frequency value \( (f) \) and the number of motor polishes \((2p)\), which are as follows as equation 10 [19].

\[
n_r = 120 \frac{f}{2p}
\]

(10)
Based on the motor rotational speed values, the angular synchronous speed value can be calculated by equation 11 [19].

\[ n_s = \frac{2\pi}{60} n_r \]  

(11)

In motor performance, there are some power losses. The power losses analyzed on this motorbike are the friction losses in bearings \( (P_{fr}) \), The armature winding losses \( (P_a) \), and stray losses \( (P_{stray}) \). The friction losses in the bearings calculated using the following equation 12 [19].

\[ P_{fr} = k_{fb} m_r n_r \times 10^{-3} W \]  

(12)

Where, \( k_{fb} \) is the coefficient bearings \( m_r \) is the mass of the rotor, and \( n_r \) is the speed turn the motor. The armature winding losses calculated using the following equation 13 [19].

\[ P_a = m_1 I_a^2 R_1 \]  

(13)

In which, \( m_1 \) = the number of motor phases; \( I_a \) = the motor current; and \( R_1 \) = the motor winding resistance per slot. Stray losses are still a difficult problem to analyze using formulas with accurate results. The analysis of stray losses assumed to be 1% of the mechanical power of the motor as equation 14 [19].

\[ P_{stray} = 0.01 P_m \]  

(14)

It is essential to know the power value electromagnetic in calculating the amount of mechanical power and input power. Electromagnetic energy calculated by the following equation 15 [19].

\[ P_{eim} = \frac{2\pi}{60} n_s T_d \]  

(15)

It is required, mechanical power calculation to determine the efficiency of the motor. Mechanical power is the power of the engine minus all power losses. The amount of the mechanical strength of the motor calculated as equation 16 [19].

\[ P_m = P_{eim} - P_{fr} \]  

(16)

Torque motors rated shaft torque or a motor torque generated from mechanical power. The estimated shaft torque value calculated using the following equation 17 [19].

\[ T_{sh} = \frac{P_m}{2\pi \left( \frac{n_s}{60} \right)} \]  

(17)

The calculation of motor input power is necessary to determine the value of motor efficiency. Motor input power is the electromagnetic power of the motor and all power losses. Input power values calculated through the following equation 18 [19].

\[ P_{in} = P_{eim} + P_a + P_{stray} \]  

(18)

It can be calculated the value of motor efficiency through the following equation 19 [19].

\[ \eta = \frac{P_m}{P_{in}} \times 100\% \]  

(19)

2.3 Design for manufacturing

Torque on the motor based on Fleming’s left-hand rule. If the conductor electrified, the force would arise [20]. Based on the Left Hand Rule Fleming Law, the position of the permanent magnet on the rotor is adjusted to create a magnetic field as shown in the Figure 1 and the force is under
the view of the winding. The rotation can be formed continuously due to the power and magnetic field created.

Figure 1. Magnetic flux in a motor

There are three terminals connected by a voltage source in a three-phase motor. Motor slots have Y-connected as shown in the Figure 2. There are two slots in each phase connected in series. This study uses a hall effect sensor. The sensor is used as a permanent magnet position detector and generates a feedback signal to the motor driver. The number of hall effect sensors used is 3. Each sensor positioned between 2 coils. The whole motor prototype was designed before printing (Figure 3). The design performed to determine the shape of the motor according to the specifications obtained.

Figure 2. The Y-connected slots circuit configuration
The motor needs to be designed in advance to plan the shape of the engine according to the design calculations performed. Figure 4 shows the stator and rotor motor of 3D design. In this study, the permanent magnets on the rotor arranged in the USUS. Each coil per slot is 175 turns. Based on the results of the design and design of the motor, known motor specifications as shown in the Table 1.

| Table 1. Motor parts specifications |
|------------------------------------|
| Slots | 6 | slots |
| Pole | 8 | poles |
| Phase | 3 | phase |
| Number of turns | 175.9 |
| magnet material | NdFeB |
| The diameter of the permanent magnet | 0.0075 | m |
| Magnet thickness | 2 | mm |
| The magnetic flux of the permanent magnet | 0.0001 | Wb |
| Coil span | 4 |
| Mass of rotor | 0.1 | kg |
3. Result and discussions

Figure 5. Tests on prototype AFPM BLDC DR 6S8P Motor

The test configuration is carried out by measuring the voltage value between the driver’s output phase, motor current, driver frequency, and motor rotational speed, as depicted in Figure 5. Based on speed and frequency testing, obtained data as seen in Figure 6. The higher the frequency of motor drivers, the more fast motor rotational speed, The test results obtained a maximum speed of 2365 Nm at 157 Hz and a motor input voltage of 24 V. The lowest measured rate is 1031 rpm with a frequency of 68 Hz driver and motor input voltage of 10.6 V.

Figure 6. The relation between rotational speed (rpm) and frequency (Hz)
Based on the rotational speed testing and analysis of rotational speed calculation, a comparison graph is obtained. The two results are as shown in the Figure 7. Based on the measurement results and analysis of the calculation of motor rotational speed, the percentage of motor speed errors is less than 2%. The highest error is 1.08% at speeds of 1031 rpm and 1865 rpm, while the lowest error is 0.13% at 1577 RPM and 2313 RPM. Based on the results of the analysis of torque calculations, the following data are obtained in the Figure 8.

Based on the results of the calculation analysis, the highest torque is obtained 0.055 Nm at the input voltage of 24 V, and the lowest measured 0.035 at the input voltage of 10.6 V. Based on the
results of the analysis of the calculation of input power, mechanical power, and efficiency obtained the following in the Figure 9.

![Figure 9](image_url)

**Figure 9.** Experimental results for rotational speed (rpm) and efficiency (%)

Based on the results calculation analysis, the highest mechanical power is 13.54 W at 24 V input voltage. The lowest is 3.79 W at 10.6 V. input voltage. The highest input power is 19.24 W at 24 V input voltage, and the lowest is 6.25 at 10.6 V. input voltage. The highest efficiency value is 70.53 % at 23 V input voltage and lowest at 60.59% at input voltage 10.6 V. This design has a target motor specification with 2000 rpm motor rotational speed with 22.2 W motor mechanical power, and 1.5 A motor current. The test results show that the maximum motor speed is 2365 rpm, 13.54 W mechanical power, and motor current 1.47 A. The speed value of the test results 365 rpm higher than the target. However, the automatic power value is smaller than 8.66 W, and the current motor value is 0.03 A lower than the goal.

4. **Conclusion**

Based on the results of testing and analysis of calculations performed, the application of the motor application needs to pay attention to the materials used, to reduce power losses. The AFPM BLDC DR 6s8p motor has an efficiency range of 60% to 71%, maximum rotational speed at an input voltage of 2364 rpm.

5. **Reference**

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