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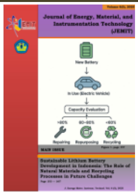

Enchancing BLDC Motor Performance with Wheel-Hub Design by Modify Coil Configurations

Rifki Dwi Putranto*, Isa Hafidz, Henko Kholima, and Nur Wahyuni Putri

Electrical Engineering Study Program, Telkom University, Surabaya Campus, Jl. Ketintang No.156, Surabaya 60231, East Java, Indonesia

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***Keywords:** BLDC motor, Wheel-Hub contruction, Winding configuration, Motor efficiency, torque and speed.*

Abstract

This paper presents an analysis of the design method of a BLDC (Brushless DC) motor with a wheel-hub structure. This study examines how variations in winding configuration affect motor performance. A 650W wheel-hub BLDC motor will be tested by modifying its stator design, including variations in the number of wires, the number of parallel circuits, and the diameter of its conductor. The test focuses on the effect of these changes on the torque, efficiency, output power and rotational speed of the motor.The test was carried out using standard sized wires. The results show that appropriate winding arrangements can increase motor torque and speed. When the parallel circuit configuration is used, the motor efficiency increases and the wire diameter is optimized. Based on the design implementation carried out, the 650W hub-type BLDC motor tested was able to achieve a maximum power of 956W, a maximum speed of 477 rpm, and a maximum torque of 41 Nm. In addition, the highest efficiency achieved was 86% at a torque of 31.8 Nm, a speed of 239 rpm, and a power of 956W.The results of this study emphasize the importance of proper winding configuration in optimizing motor performance. This winding configuration selection procedure is expected to be a reference in the manufacture of wheel-hub BLDC motors.

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***Kata kunci:** Motor LDC, konstruksi roda-hub, konfigurasi winding, efisiensi motor, torsi dan kecepatan.*

Abstrak

Makalah ini menyajikan analisis metode desain motor BLDC (Brushless DC) dengan struktur roda-hub. Studi ini mengkaji bagaimana variasi konfigurasi winding mempengaruhi kinerja motor. Sebuah motor BLDC roda-hub 650W akan diuji dengan memodifikasi desain statornya, termasuk variasi jumlah kawat, jumlah sirkuit paralel, dan diameter konduktornya. Uji coba difokuskan pada efek perubahan ini terhadap torsi, efisiensi, daya keluaran, dan kecepatan putaran motor. Uji coba dilakukan menggunakan kawat berukuran standar. Hasil menunjukkan bahwa pengaturan winding yang tepat dapat meningkatkan torsi dan kecepatan motor. Ketika konfigurasi sirkuit paralel digunakan, efisiensi motor meningkat dan diameter kawat dioptimalkan. Berdasarkan penerapan desain yang dilakukan, motor BLDC tipe hub 650W yang diuji mampu mencapai daya maksimum 956W, kecepatan maksimum 477 rpm, dan torsi maksimum 41 Nm. Selain itu, efisiensi tertinggi yang dicapai adalah 86% pada torsi 31,8 Nm, kecepatan 239 rpm, dan daya 956W. Hasil dari studi ini menekankan pentingnya konfigurasi lilitan yang tepat dalam mengoptimalkan kinerja motor. Prosedur pemilihan konfigurasi lilitan ini diharapkan dapat menjadi acuan dalam pembuatan motor BLDC hub roda.

1. Introduction

The transportation industry is one of the largest contributors to greenhouse gas emissions. The solution requires the rapid electrification of land vehicles (Zheng et al., 2022). Achieving this requires operational and energy-saving techniques, commercialization, and regulations that encourage a shift to low-carbon transportation modes. Electric vehicles do not produce direct emissions, but their power source can contribute to emissions if it is derived

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* Corresponding author.
E-mail address: rifkidwi@telkomuniversity.ac.id

from fossil fuels (Zhao et al., 2025; Veza et al., 2023). Therefore, increasing renewable energy is necessary to reduce environmental impacts (Rani & Jayapragash, 2024).

Brushless DC (BLDC) motors have advantages, including high torque, low-to-weight ratio, efficiency, and low noise (Pal, 2021; Yang et al., 2020). Compared with other motors, BLDC motors are expected to have higher efficiency, better torque-to-weight ratio, and lower operational noise (Haghighat et al., 2018). These motors have a stationary magnetic flux between the rotor and stator, allowing the motor to operate at a power factor of unity. BLDC motors are controlled using electronically commutated motor drives, where each phase of the motor is controlled by a closed-loop controller (Mohanraj et al., 2022).

One method to improve BLDC motor performance without requiring a completely new design is modifying the number of turns in the stator. Increasing the number of turns or changing the configuration can affect the back-EMF, torque, and efficiency of the motor, thus improving electric vehicle performance at a more cost-effective rate than manufacturing a new motor. In high-speed BLDC motors, the zero-EMF crossing point (ZCP) is used to detect the commutation point. The ZCP method has limitations when the motor is running. At zero range and low speeds, the back-EMF is not high enough to affect the ZCP accuracy. Strategies to address this have been discussed in research (Shi et al., 2020). Furthermore, a sensorless ZCP method with a low-pass filter is also needed to avoid errors in commutation point readings (Smółka, Firych-Nowacka, & Wiak, 2022). Several other factors that can affect ZCP readings include asymmetric motor parameters, non-ideal EMF shapes, and armature reaction (Kurniawan & Nauri, n.d.; Gecer et al., 2021; Shen & Tseng, 2003).

Sensorless flux-linkage-based schemes may be unsuitable for high-speed motors because they require high sampling rates and are computationally demanding. Therefore, one solution is to use a Hall sensor. This approach has been widely used in high-speed BLDC motors because it is unaffected by machine parameters, EMF waveforms, and armature reaction (Saed et al., 2022; Sun et al., 2020). Furthermore, the absence of high-frequency noise allows for negligible LPF influence.

Despite their widespread applications, BLDC motors still face challenges in improving efficiency and refining control strategies to enhance performance and reliability. This paper describes a design methodology analysis for a BLDC motor with a wheel-hub construction. This design considers the configuration of the number of parallel circuits and variations in winding diameter. Torque, output power, and rotational speed are considered in the analysis process. The contributions are presented as follows:

1. Testing a 650 W BLDC wheel hub motor using stator design changes with varying wire counts, including the number of parallel circuits and conductor diameter.
2. Analyzing changes in stator design with varying wire counts, particularly the number of parallel circuits and conductor diameter, on torque, efficiency, output power, and rotational speed.
3. Obtaining an optimal design from the experimental results for analysis to improve torque, efficiency, output power, and rotational speed.

This part of the article was divided into several parts. Chapter 2 describes the requirements for motor design. Chapter 3 describes the result of the motor design test scheme. Chapter 4 discusses the test results. Chapter 5 discusses the conclusions of the study. This study introduces additional variations of the winding parameters, resulting in a better magnetic field distribution, which leads to an increase in torque without the need to enlarge the motor's physical size.

2. Research Methods

2.1 Requirements For Motor Design

This research began with data collection on the specifications of an existing BLDC in-wheel hub motor as a basis for design. The first stage was a design simulation using Motor-CAD software, inputting existing motor parameters such as rotor diameter, number of poles, stator size, and initial winding configuration (**Figure 1**).

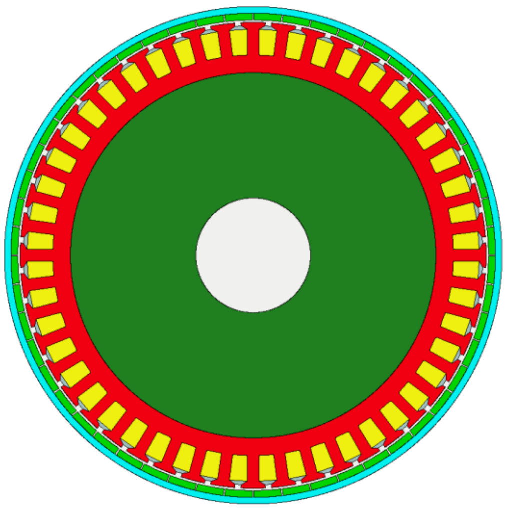

Figure 1. Design WHM

Next, the number of stator windings was modified according to the planned performance improvement scenario. After the design was updated, thermal and electromagnetic simulations were performed in Motor-CAD to evaluate the effect of the winding changes on torque, power, efficiency, and heat distribution.

The simulation results were compared between the initial and modified designs to determine whether there was a significant performance improvement. If the simulation results met the improvement criteria, the next stage was the construction of a physical prototype for experimental testing under real-world load conditions to validate the simulation results.

Previous works that the author had done were related to the study of optimizing a 40-pole, 42-slot SPMSM to replace a 0.65 kW in-wheel hub motor in an e-scooter [20]. The rotational speed of a wheel-hub brushless motor has units of radians per minute (rpm), representing the rotational speed of the rotor. The speed of rotation was affected by the operating voltage, the strength of the magnetic flux connection, and the number of wires. These conditions can be written as follows.

$$rpm = \frac{f \times 60 \times 2}{pole} \tag{1}$$

The output power was obtained from the rotation speed and torque. When brought to the mathematical equation can be written as follows.

$$P_{out} = T \times rpm \times \frac{2\pi}{60} \tag{2}$$

Efficiency was the percentage ratio of output power to input power. Efficiency can be written as follows.

$$\mu = \frac{P_{out}}{P_{in}} \times 100\% \tag{3}$$

Torque was a rotational force from the formation of power, speed, and constants. To calculate the torque value obtained from the equation

$$T = \frac{60 \times P_{out}}{2\pi \times Rpm} \tag{4}$$

In BLDC motors, an important parameter to consider was the number of polishes (**Figure 2**). The more poles, the smaller the stator diameter relative to the rotor. Copper loss can be reduced when the number of polishes increases because it reduces the cable length. However, an increase in the polish will cause the switching frequency to be higher, thereby increasing iron losses. The increasing loss was corrected by reducing the stator back iron.

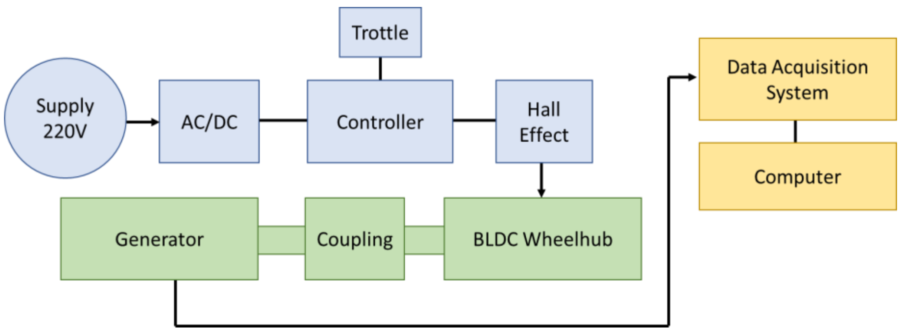

Figure 2. Scematic of the BLDC Wheel-hub motor testing circuit

3. Results and Discussions

3.1 Motor Design Manufacturing and Testing Scheme

In this paper, a typical motor design procedure was followed. The first step was to design a motor to analyze the number and diameter of the wire to be developed. Then, data was collected from the stator rotor section. The motor used was a 650W BLDC wheel-hub. The type of conductor used was copper, with a diameter between 0.6 to 0.8 mm. In addition to testing the parallel variations of the conductors with the installation of 7 to 10 parallels with 3 winding turns. Next was the analysis of the simulation results of torque and efficiency values, rotational speed, and output power, which were affected by the number and diameter of the wire. After getting the best results, the next step was to do a trial run to get the results from the implementation of the research.

The test in this paper was carried out in several stages as follows: connecting AC voltage, converter on 48V power supply, installation of coping between the generator and the BLDC hub motor, the output data results from the generator which turns on a load of 1 KW on the lamp which was serialized to 100 W which results in the form torque, speed, output power, and laptop efficiency connected to sensors that have been paired into one Arduino.

The working principle in **Figure 1** on the schematic uses an AC source with a voltage of 220V to run a brushless DC wheel-hub motor. After connecting to a 220V AC voltage source, convert it to DC 48V to run a 650W DC brushless wheel-hub motor with a capacity of 48V. After being connected by the converter, it will then be controlled by a drive controller with a current motor to regulate the amount of incoming current so that the rotation of the motor can be adjusted accurately. In the data collection process, find the value of torque, rotational speed, output power, and efficiency with the help of motor CAD software.

Brushless wheel-hub DC motors were connected to a timing belt made of rubber to a generator on the DC brushless motor. It uses a throttle or gas handle to produce low to high rotational speeds, resulting in torque Nm, output power W, efficiency, and rotational speed rpm, on data retrieval of wheel-hub type DC 650W brushless motors with the help of tools that produce the required data connected to a laptop.

The converter can increase and decrease the voltage. In converting, a parallelized 12 (V) power supply and a 220V AC voltage will be connected to the controller with a converter equal to the voltage according to the motor parameters of 48V. The power supply converter used in this final project has a capacity of up to 144 V.

Table 1. Wheel-Hub Type DC Brushless Motor Default Parameters

Number	Parameter	Value	Unit
1	Voltage	48 V	Volt
2	Power	650 W	Watt
3	Roll type	Parallel	Parallel
4	Number of stator slots	63	-
5	Number of poles	56	-
6	Rotor thicness	7.9	Milimeter

3.2 Motor Contruction Manufacture

The first step in analyzing the number and size of wires that affect the torque, output power, efficiency, and rotational speed of a brushless DC motor was to determine the parameters used as a reference in this final project in **Table 1**. The default motor parameters were 0.7 mm in diameter and 7 parallel wires with 7 turns surrounding each stator slot.

Winding the 650 W wheel-hub BLDC motor wire was a winding process from the initial to the final step. Wire winding process functions to implement the winding turn results determined from a diameter of 0.8 mm and 7 wires parallelized with 3 turns. For more details, the process of winding the wire to the stator slot wire can be seen in **Figure 3**. **Figure 3** shows the initial process until the winding conditions are complete. When the winding process is complete, attention must be paid again to the winding, in which the condition of the wire should not touch the stator iron plate.

Figure 3. DC wheel-hub motor construction on (a.) rotor and (b.) stator

3.3 Variation On Widing Turn Configuration

During the winding process of the 650 W BLDC wheel-hub motor, special attention must be given to ensure that the wire does not come into contact with the stator iron plate, as this could impact performance and longevity. The motor testing process utilized a HUB-type 650 W BLDC motor, with data collection automated through PLX software integrated into an Excel-based system. A 48 V power supply served as the main power source, while a 100 W generator, with a total load capacity of 1 kW, was connected to lamps acting as the load.

The motor and generator were linked via a timing belt, allowing for controlled adjustments in rotation speed through a throttle (gas handle). Additionally, a controller was used to establish connections between the motor, throttle, sensors, and power supply, ensuring efficient system operation. Data retrieval was facilitated by a laptop connected to a black box, which housed an Arduino and multiple sensors. The use of PLX software enabled real-time monitoring and recording of motor performance parameters. As illustrated in **Figure 4**, this setup provided a structured and precise approach to evaluating the efficiency, torque, and speed characteristics of the BLDC motor under varying load conditions. The output power of a 650 W DC brushless motor has a relationship between torque and rotational speed. The output results can be found with a calculation formula that has previously been tested with motor CAD software.

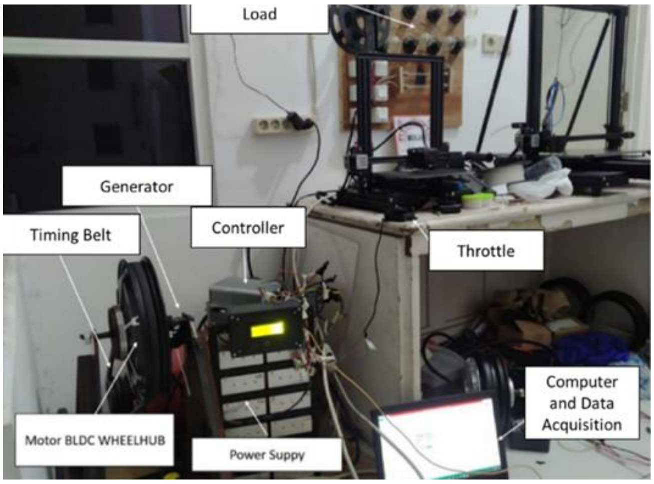

Figure 4. Testing BLDC Motor 650

3.4 Motor Testing with Variation Widing Turn

Figure 5 illustrates the impact of different coil diameters on motor performance, with wire sizes of (a) 0.6 mm, (b) 0.7 mm, and (c) 0.8 mm, tested with 7, 8, and 9 parallel winding variations, respectively. The results show that increasing the number of parallel windings increases torque but can also reduce the rotational speed of the BLDC. In addition, the use of larger coil diameters in the same configuration results in higher torque due to lower electrical resistance and better current carrying capacity.

Figure 6 presents the correlation between output power and rotational speed for the different winding diameters tested. The results show that as rotational speed increases, the power output rises until reaching a peak point. Beyond this peak, power output begins to decline while rotational speed continues to increase. This behavior suggests that at higher speeds, losses such as increased resistance, core losses, and back electromotive force (EMF) affect motor performance, limiting the achievable power.

Optimizing winding parameters, such as coil diameter and parallel winding configurations, was essential for achieving the desired performance characteristics, depending on the specific application requirements.

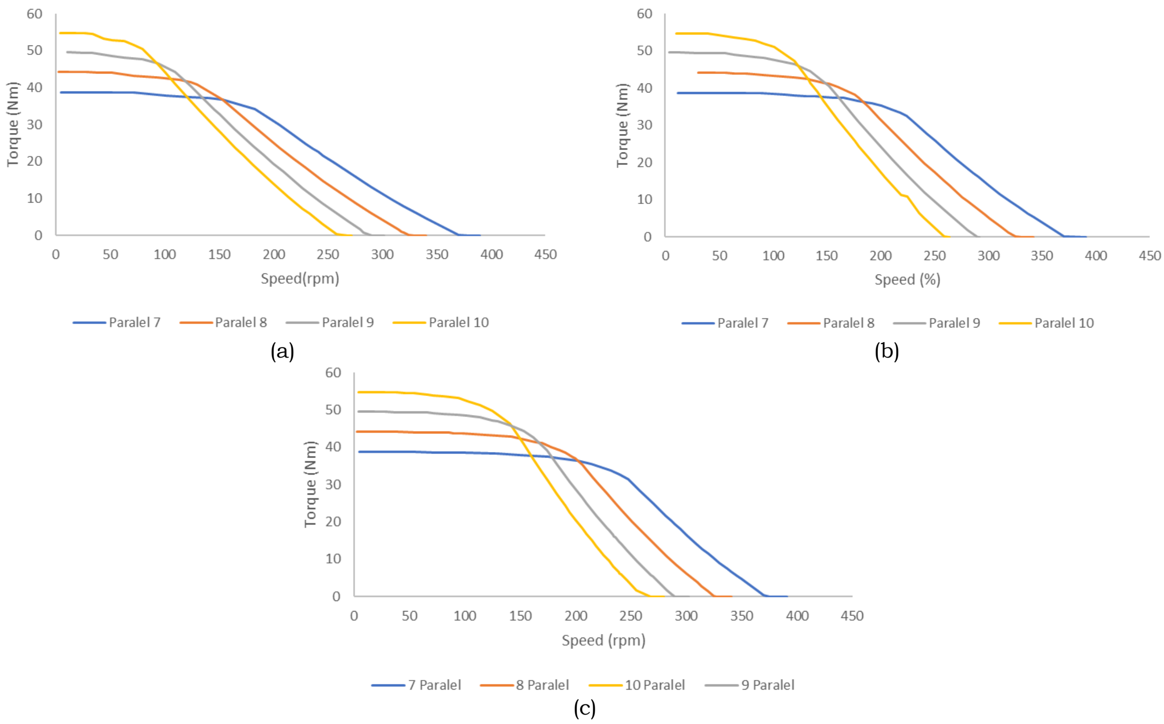

Figure 5. Torque response and rotational speed of the motor on winding diameters of (a.) 0.6 mm, (b.) 0.7 mm, and (c.) 0.8 mm, respectively, with variations in the number of parallels of 7, 8, and 9

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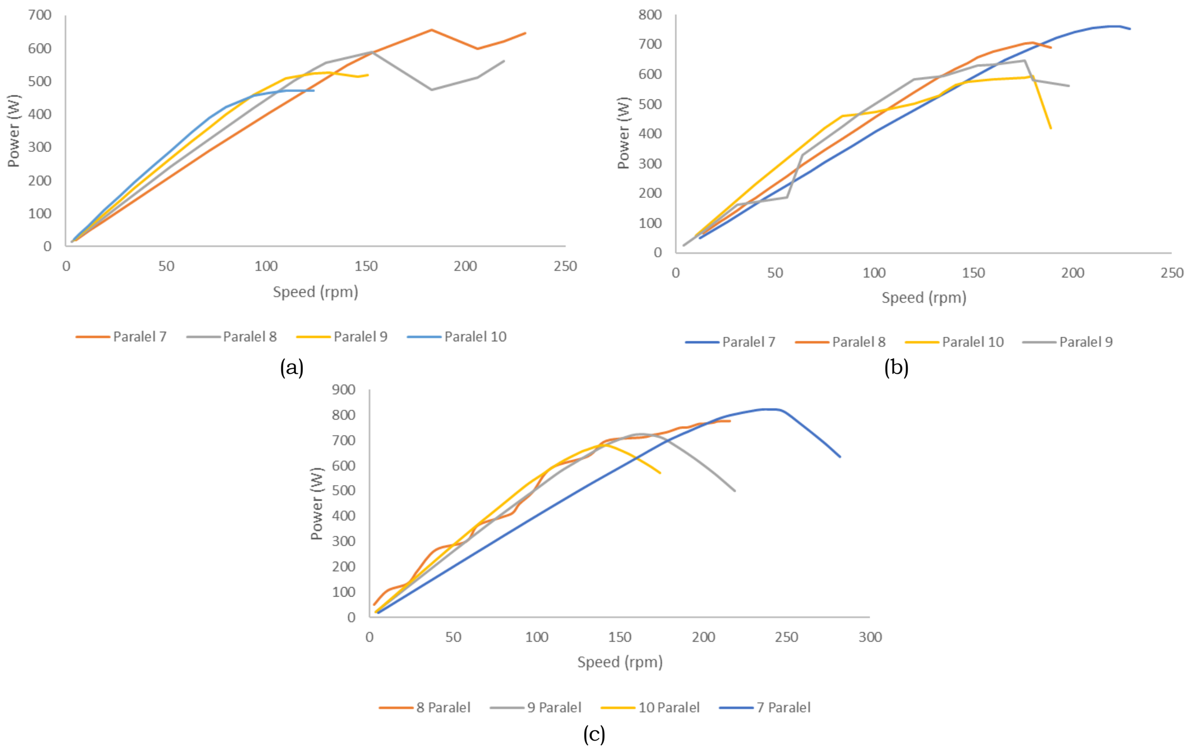

Figure 6. The response of the output power and rotational speed of the motor on winding diameters of (a.) 0.6 mm, (b.) 0.7 mm, and (c.) 0.8 mm, respectively, with variations in the number of parallels 7, 8, and 9

3.5 Motor Testing with Proposed Widing Combinations

From the previous work that has been done, it can be observed that the number of parallel windings of 7 in combination with 3 turns has the highest power and speed values compared to the other combinations. Referring to the diameter of the conducting wire, the diameter with the most significant torque was 0.8mm. The next step was to do direct testing. It can be seen in **Figure 7**, where the peak speed was obtained for maximum torque at 40,477 Nm, with a speed of 47rpm.

The response of rotational speed, torque, and output power of the proposed BLDC motor winding configuration is shown in **Figure 8**. The motor has a torque of 6.48 Nm at a rotational speed of 477 rpm. Then, the motor load was increased until the torque increased by 41 Nm. Meanwhile, the output power generated at the initial torque was 6.4 Nm with a power value of 589 W. Then, it was tested with an additional load until the peak torque reached 205 W; however, when the BLDC HUB motor can work up to produce a power of 956 W.

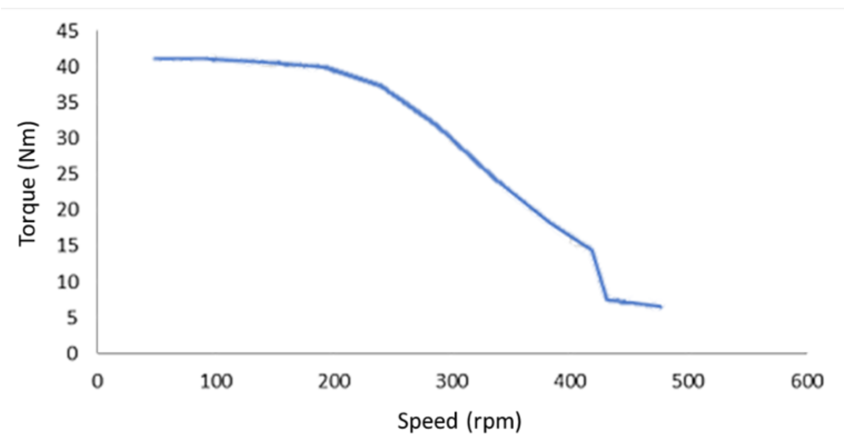

Figure 7. Response of torque and speed test

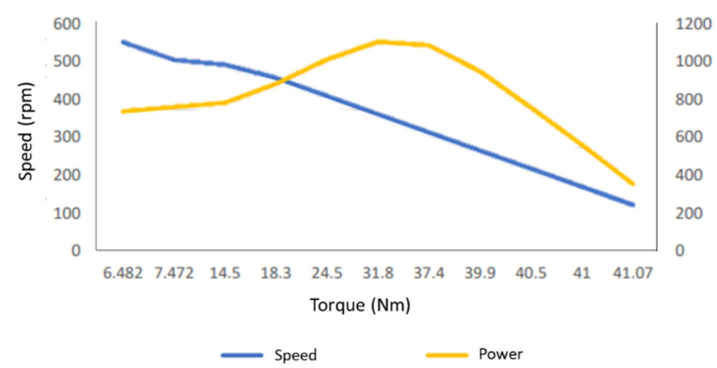

Figure 8. Response of rotational speed, torque, and output power of the proposed BLDC motor winding configuration

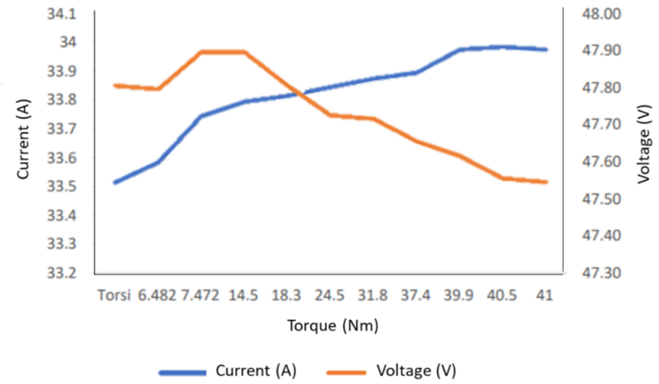

Figure 9. Current, voltage, and torque response of the proposed BLDC motor winding configuration

Motor testing also shows the voltage and current results on the motor at the time of measurement, as shown in **Figure 9**. **Figure 9** shows that at the beginning of the loading torque of 6,482 Nm, the voltage at the motor terminal reaches its maximum point at 47.8 V with a current reaching 33.8 A. maximum 41.07 Nm.

The design used considers the analysis of the number of parallel circuits and variations in the diameter of the windings. From the test result, the larger the diameter, the greater the output power and efficiency. As for the number of wires that affect the torque value, when the number of wires was added, the torque value was also higher, but the resulting rotational speed decreased. In general, it can be seen that the greater the number of parallel windings, the more torque increases while the rotational speed decreases. With the same configuration but different diameters of the conducting wires, the larger the diameter of the coil, the greater the torque obtained. Then, the higher the motor rotational speed, the greater the required power up to the maximum peak point. The power decreases at a certain rotational speed, but the speed still increases. It can be observed that the number of parallel windings of 7 pieces combined with 3 turns has the highest power and speed values compared to the other combinations. Referring to the diameter of the conducting wire, the diameter with the most significant torque was 0.8mm. From the implementation result, the maximum motor output power of 956 W, a maximum speed of 477 rpm, and a maximum torque of 41 Nm. The motor can also provide a maximum efficiency of 86% at 31.8Nm of torque, 239 rpm speed, and 956 W of power.

4. Conlusion

This paper describes the analysis of the design methodology of a brushless DC (BLDC) motor designed with a Wheel-hub type construction. The design used considers the analysis of the number of parallel circuits and variations in the diameter of the windings. The results of the implementation of the wheel-hub 650 W type BLDC. From the test, the larger the diameter, the greater the output power and efficiency. When the number of wires was added, the torque value was higher, but the rotational speed decreased. It can be seen that the greater the number of parallel windings, the more torque increases while the rotational speed decreases. With the same configuration but different diameters of the conducting wires, the larger the diameter of the coil, the greater the torque obtained. Then, the higher the motor rotational speed, the greater the required power up to the maximum peak point. From the proposed implementation result, the maximum motor output power of 956 W, a maximum speed of 477 rpm, and a maximum torque of 41 Nm. The motor can also provide a maximum efficiency of 86% at 31.8 Nm of torque, 239 rpm speed, and 956 W of power. Future work that can be done next is to optimize the dimensions of the motor to be smaller with specifications that same. In addition, it was possible to test the reliability of the motor with variations in load, temperature, and humidity.

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