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Design optimization analysis on the performance of BLDC motors on electric bicycles

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Abstract. Optimal design results in maximum motor performance. This type of BLDC motor has undergone design innovations such as surface-mounted permanent magnet (SPM) with variants such as: radial magnet, rectangular magnet, and bread-loaf. The position of the outer rotor is a motor design that is commonly applied to electric bicycles. The position of the magnet attached to the side of the electric motor body allows for superior torque performance. In this paper, we present an analysis of the BLDC motor on an electric bicycle that has been implemented. The motor used uses the outer rotor SPM geometry with a power of 500W. Parameter changes made are slot depth, tooth width, and comparing the basic design with the Halbach array design using 2 and 3 magnets. Changes in these parameters have an impact on power, torque, speed, and efficiency.

1. Introduction

The development of electric motors for transportation has entered the realm of design. Optimal design results in maximum motor performance. This is shown from the results of testing the electric motor. Where, the design improvement shows an increase in performance. The types of electric motors that are often used are DC motors, induction motors, and brushless DC motors (BLDC). DC motor does not experience a significant increase. Brushed DC motors are still the main obstacle in increasing efficiency. Brushed DC motors cause power losses when the DC motor is operated. DC motor design innovations were developed according to the circuit used, such as: permanent magnet, series, shunt, and separately excited. The geometric design of the DC motor has not changed.

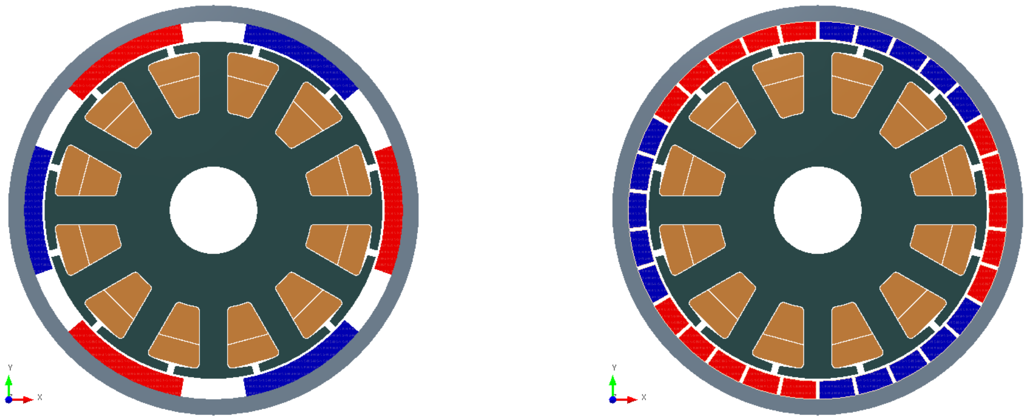
The design of the induction motor underwent a good geometric design change. The development of the geometric design includes a synchronous reluctance motor (Sync-RM). It is claimed that the motor using the Sync-RM geometric design has higher efficiency than the squirrel-cage induction motor. In transportation applications, both induction motors and Sync-RM must use high voltages. It takes a lot of battery cells that must be carried by the vehicle. In the implementation of small transportation applications such as bicycles and scooters, the use of induction motors and Sync-RM is not appropriate.

This type of BLDC motor has undergone design innovations such as interior permanent magnet (IPM) and surface-mounted permanent magnet (SPM) [1]–[3]. The geometric design of IPM has variants such as: inset magnet, spoke magnet, halfback-array, v-magnet. SPM geometric design has variants such as: radial magnet, rectangular magnet, and bread-loaf [4], [5]. In addition to this design, the rotor position is adjusted into 2 types, namely the inner rotor and outer rotor. Inner rotor design, the position of the magnet attached to the rotating shaft. While the outer rotor design, the position of the magnet attached to the side of the electric motor body. Each design has the advantage of increasing power, torque, speed, and efficiency [6]–[9]. The implementation for BLDC motor applications has many advantages including use in heavy vehicles, public transportation, bicycles, to scooters. The voltage requirement for the implementation of a BLDC motor is 24-400 VDC [10].

In this paper, we present an analysis of the BLDC motor on an electric bicycle that has been implemented. The motor used uses the outer rotor SPM geometry with a power of 500W. The design parameters are based on the existing BLDC motor. Parameter changes in the form of slot depth, tooth width, and comparing the basic design with the halbach array design using 2 and 3 magnets. Parameter changes were made to obtain the performance characteristics of each different design. Design differences have an impact on differences in performance of power, torque, speed, and efficiency. The results of the analysis will explain the classification of design parameters in improving the performance of power, torque, speed, or efficiency.

2. Study of literature

The simulation process on the design of the electric bicycle BLDC motor is carried out by identifying the design parameters of the electric motor. Figure 1 shows the outer rotor SPM design which is widely implemented on electric bicycles. Figure 1 (a) shows the design of the BLDC SPM outer rotor radial magnet. This design uses different poles, the position of the magnet is perpendicular to the opposite side. Figure 1 (b) shows the BLDC SPM outer rotor halbach array design with 4 magnets. This design uses the same pole with a total of 4 magnets, after which there are 4 magnets towards the opposite pole. The number of opposite poles is according to the design.



(a) (b)

Figure 1. (a) Design of BLDC SPM outer rotor radial magnet, (b) Design of BLDC SPM outer rotor Halbach array

The use of the BLDC SPM outer rotor design is to have a large enough torque at a speed that suits the needs of an electric bicycle. In order to determine the size of a BLDC SPM outer rotor that will produce a required torque (T), the following scaling law can be used:

$$T = kD_r^2L \quad (1)$$

Where, k is a constant, D_r is the rotor outer diameter and L is the stack length using

$$L = rD_s \quad (2)$$

$$D_s = \frac{D_r}{f} \tag{3}$$

Where, D_s is the stator outer diameter, r is motor aspect ratio, f is rotor-stator ratio, (1) can be expressed as

$$T = k\frac{r}{f}D_r^3 \tag{4}$$

In the context of Sizing, power balance between the input power P_i, the mechanical power P_m and the windings losses P_l is expressed as

$$P_i = P_l + P_m \tag{5}$$

Where the input power (P_i) is given by

$$P_l = N_{ph}V_{rms}I_{rms}\cos\phi \tag{6}$$

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}} = \frac{1}{\sqrt{2}}\frac{V_{line}}{\sqrt{3}} \tag{7}$$

Where, N_{ph} is number of phases, V_{rms} is rated voltage, I_{rms} is rated current, $\cos\phi$ is power factor, V_{peak} is peak voltage, V_{line} is supply voltage. The mechanical power (P_m) is given by

$$P_m = \omega T = \frac{2\pi}{60}v_{rpm}T \tag{8}$$

Where, v_{rpm} is rated speed. The losses (include the Ohmic loss in the coil sides only, the losses in the end turns as well as the core losses are not taken into account) are given by

$$P_l = N_sR_sI_{rms}^2 \tag{9}$$

$$R_s = NN_l\frac{L}{\sigma A_w} \tag{10}$$

Where, N_s is number of slots, N_l is number of layers, σ is coil material conductivity, A_w is conductor area. The efficiency of BLDC motor is given by

$$\eta = \frac{P_m}{P_i} \tag{11}$$

3. Methodology

Figure 2 shows the research methodology carried out to obtain performance from power, torque, speed, and efficiency. The first step is to identify the design parameters of the BLDC motor. After identification, the next step is to perform a simulation based on the basic design that has been made. The results of the basic design are used as the basis for the power, torque, speed, and efficiency of the BLDC motor. For the next step, the size of the slot depth, tooth width, and magnet configuration is changed by using a Halbach array. After making design changes, the simulation process is carried out by comparing the speed, torque, power, and efficiency performance of the BLDC motor. The designs compared have the advantages of various BLDC motor performances. The optimal design is obtained based on a comparison with how much the BLDC motor design performance can be improved.

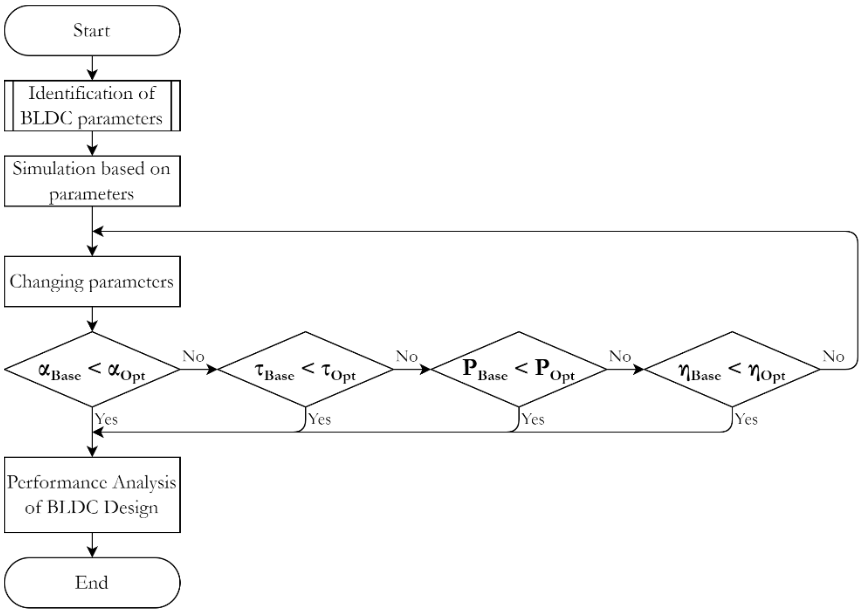


Figure 2. Research methodology

3.1. Parameters

Table 1 shows the baseline parameters for the BLDC motor design which is simulated using software. The value of each parameter has been validated using a measuring instrument. The BLDC motor used is a motor used in electric bicycles. Figure 3 shows the analyzed outer rotor SPM BLDC motor.

Table 1. Baseline of BLDC motor design parameters

No	Parameter	Value
1.	Supply voltage (V)	48
2.	Rated current (A)	15
3.	Rated speed (rpm)	600
4.	Outer diameter (mm)	229
5.	Air gap thickness (mm)	1
6.	Stack height (mm)	27
7.	Rotor location	Exterior
8.	Number of poles	46
9.	Number of slots	51
10.	Magnet thickness (mm)	3
11.	Magnet width (mm)	13,5
12.	Slot depth (mm)	15
13.	Slot opening width (mm)	5
14.	Tooth width (mm)	4,5
15.	Strand diameter (AWG)	24
16.	Number of strands in hand	10
17.	Number of turns	5
18.	Fill factor (%)	26,93

Figure 3. BLDC SPM motor outer rotor

3.2. Design

Table 2 shows the design scenarios tested in the simulation. Design 1 is the basic design of an electric bicycle motor. Design 2 converts the magnet construction into a halbach array with 2 magnets. Design 3 converts the magnetic construction into a Halbach array with 3 magnets. Design 4 only changes the stator depth slot construction from 15 mm to 16 mm. Design 5 reduces tooth width to 4 mm and design 6 increases tooth width to 6 mm.

Table 2. Comparison of outer rotor BLDC SPM motor designs

Parameter	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Slot depth (mm)	15	15	15	16	15	15
Tooth width (mm)	5	5	5	5	4	6
Halbach array	1	2	3	1	1	1

4. Result and discussion

4.1. Speed and torque performance analysis

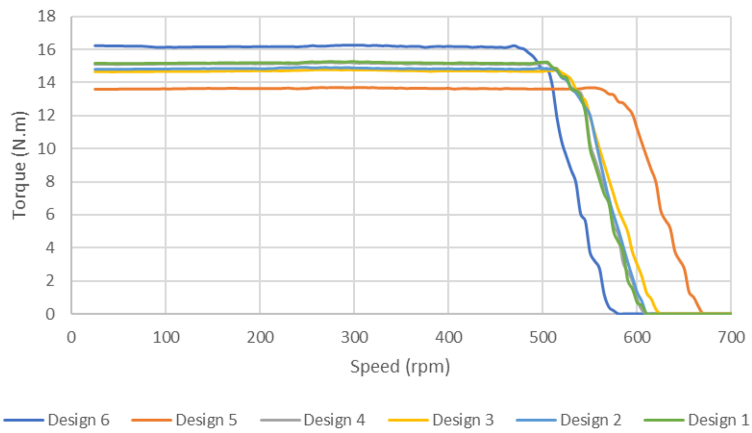
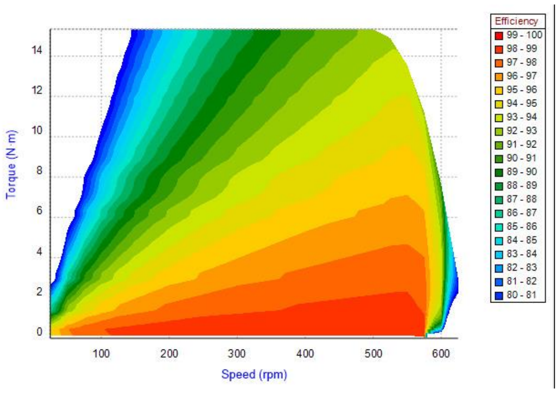


Figure 4. Torque and speed comparison on the outer rotor BLDC SPM motor design

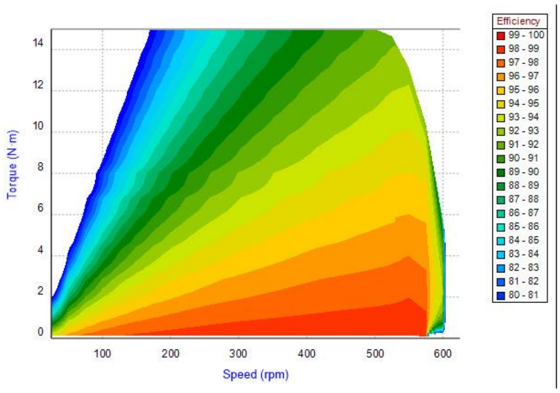
Figure 4 shows the comparison of torque vs speed for each BLDC SPM outer rotor motor design. Design 6 shows a fairly good torque performance compared to other designs. Design 5 has the advantage of increasing the speed up to 600 rpm with a torque of 12 N.m. Designs 1, 2, 3, and 4 have a speed of 550 rpm when the torque is 12 N.m. Unlike the design 6 which is capable of rotating at 515 rpm at 12 N.m of torque.

4.2. Efficiency analysis

Figure 5 shows a comparison of the efficiency mapping for each design. Please note in detail the changes that occur in each design. Changes do not change significantly, only for designs 1 and 2 have the same characteristics, while designs 3, 4, 5, and 6 have almost the same efficient map characteristics.



(a)



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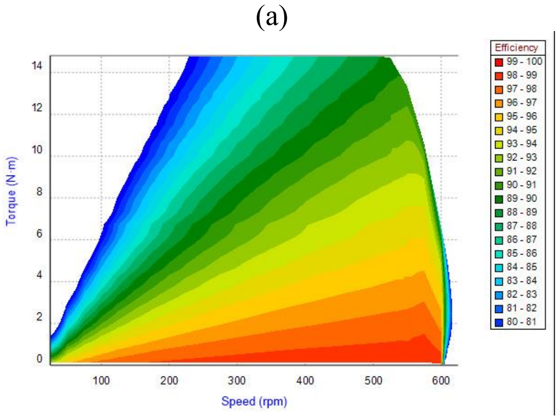
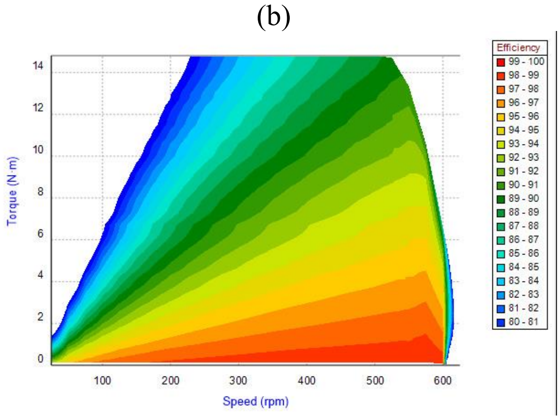
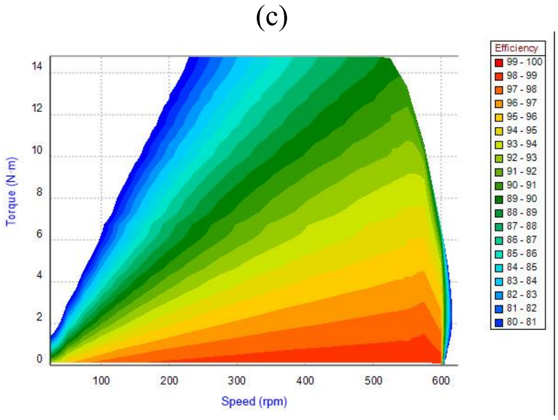


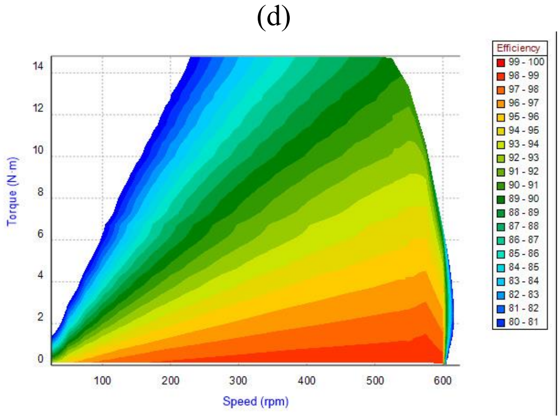
(c)



(d)



(e)



(f)

Figure 5. (a) efficiency map of design 1, (b) efficiency map of design 2, (c) efficiency map of design 3, (d) efficiency map of design 4, (e) efficiency map of design 5, (f) efficiency map of design 6

4.3. Design performance comparison

Table 3 shows a comparison of the performance analysis for each design. Comparisons include torque, RMS torque ripple, input power, output power, efficiency, and more. Based on the data, the results show that the design changes caused some of the performance characteristics of the BLDC SPM outer rotor motor to change quite a lot. The need for design changes adapts to performance requirements for certain applications such as increasing speed, torque, power, and efficiency requirements.

Table 3. Comparison of performance in each design

No	Parameter	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
1.	Torque (N·m)	15,23	14,88	14,66	15,20	13,63	14,71
2.	RMS torque ripple (N·m)	1,98	1,11	0,81	1,94	1,99	2,11
3.	Input power (kW)	0,85	0,84	0,85	0,85	0,77	0,82
4.	Output power (kW)	0,80	0,78	0,77	0,80	0,71	0,77
5.	Efficiency (%)	93,34	92,32	89,91	93,18	92,63	94,27
6.	RMS line-to-line voltage (V)	38,22	37,95	38,09	38,14	36,72	38,87
7.	RMS line current (A)	14,91	14,90	14,86	14,93	14,85	13,56
8.	RMS line-to-line back EMF (V)	30,91	30,22	29,85	30,80	27,78	32,93
9.	Power factor	0,86	0,85	0,86	0,86	0,81	0,89
10.	Supply current (A)	17,97	17,77	17,98	17,99	16,25	17,17
11.	Supply power (kW)	0,86	0,85	0,86	0,86	0,78	0,82
12.	Loss - Total (kW)	0,06	0,06	0,09	0,06	0,06	0,05

Designs 1, 2, and 3 show the comparative characteristics between the halfback-array designs of 1 magnet, 2 magnets, and 3 magnets. The arrangement of magnets in parallel has an impact on decreasing torque, power, and also efficiency at the same size magnet. The torque vs speed curve shows an insignificant increase in speed and tends to be the same. The advantages of implementing a halfback-array allow for reduced torque ripple and reduced lateral air gaps by using a smaller box magnet size.

Design 1 has the highest torque characteristic of 15.23 N.m, and design 4 has a difference of 0.03 N.m below that of 15.20 N.m. Designs 1 and 4 have higher torque characteristics than other designs. Designs 1 and 4 also have the highest power characteristics of 800 W. Design 5 in Figure 4 shows a fairly high speed characteristic of up to 600 rpm with a torque of 12 N.m. Design 6 shows a fairly high efficiency characteristic reaching 94.27% with the lowest power loss reaching 50 W. In contrast to Design 3 which has the lowest efficiency of 89.91% with a power loss of 90 W. Of course, the design that has the lowest efficiency, causing a waste of electrical energy in the battery.

If the electric motor requires a sufficiently high torque and power, designs 1 and 4 can be implemented. Whereas in electric motors that require higher speeds, design 5 can be implemented. Electric motors that have excellent efficiency can implement design 6. The application of electric motor designs is tailored to the needs of motor users to get the highest power, or the highest torque, or the highest speed, or the highest speed, or even the highest efficiency in electric motors.

5. Conclusion

In the simulation of optimizing the BLDC SPM outer rotor design, 6 designs were obtained. Where, the basic design (1) already has an optimal torque with an achievement of 15.23 N.m. Designs 1 and 4 have an optimal power output of 800 W. Design 5 has an optimal speed of 560 rpm. Design 6 has optimal efficiency with 94.27 % achievement. Based on the results of design changes, it can change the performance of the motor. However, the changes that have occurred have not focused on optimizing all output such as speed, torque, power, and efficiency. The comparison of design outputs 1 to 6 shows that if 1 output on an electric motor increase, there will be a decrease in other outputs with the same voltage and current source.

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