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Designs of PMSMs with Inner and Outer Rotors for Electric Bicycle Applications

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Abstract: ***In this paper, designs of two rotor structures of permanent magnet synchronous motor (PMSM) are proposed in order to find the suitable one to drive an electric bicycle, namely, inner rotor and outer rotor. Both motors are designed to run at a rated speed of 20 Km/h and rated power of 250 W. This paper compare the performance of both proposed motors and the comparison between them is in terms of motor size, weight, cost and efficiency. In addition, this work use the second design, which is the PMSM with outer rotor to investigate the effects of some motor parameters on motor performance; the parameters are current, advanced angle, stack length and external diameter. In this work, Motor Solve software is used to design and analyze the performance of both motors. According to the simulation and calculation results, both motors achieved the required rated speed and torque at high efficiency and reasonable cost. Nevertheless, the PMSM with inner rotor obtained the required specifications with lighter weight and smaller size than the PMSM with outer rotor. Therefore, it is a proper choice for driving an electric bicycle that has a limitation regarding the motor space. Regarding parameters' effect, the simulation figures and data show that the motor torque will increase if we increase supply current, stack length and external diameter, while speed decreases as it inversely changes with torque. Except for advance angle which helps motor to produce maximum possible torque at a higher speed.***

Keywords: Permanent magnet synchronous motor, Inner rotor, Outer rotor, Electric bicycle, Motor Solve.

1. INTRODUCTION

Over the decades, the world faces many environmental issues such as global warming and air pollution. Part of the air pollution problems are vehicles that use fossil fuels and emit harmful gases. In addition to the environmental reasons mentioned above, traffic jams and high prices of oil products also made many countries to use alternative methods of transportation that are environmentally friendly, such as electric vehicles (EVs).

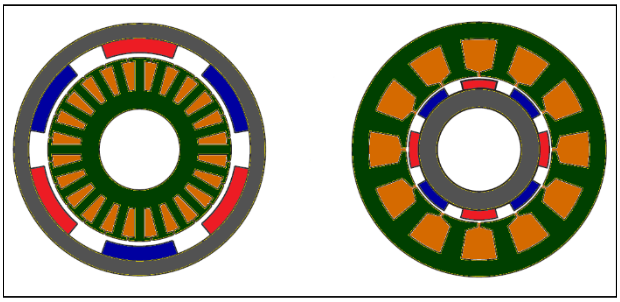
Among electric vehicles, the electric bicycle is one of the appropriate choices for short line transportation because of its attractive features such as cheap price, easy riding, convenient parking, health benefits and eco-friendly [1][2]. The bicycle's electric motor is an important and effective part, so it must be carefully designed in order to provide high efficiency, high torque and low noise. Therefore, in recent years, designers and researchers have studied different types of motors to determine the most efficient one to drive electric bicycles. The most used motors for such applications are: Switched Reluctance Motor (SRM), Permanent Magnet Flux Switched Motor (PMFSM), Multi-Flux Permanent Magnet (MFPM) and Permanent Magnet Synchronous Motor (PMSM) [1] [2] [3]. These motors share common features, as they are small in size and light in weight due to the unnecessity of brushes in their design. The rotor part of the motor of an electric bicycle can be one of the two common designs: motor with an inner rotor that can be fitted in the area between the two cranks and chain wheel, and motor with an outer rotor which can be fitted into the wheel. In this paper, two designs are proposed using PMSM type. The first one is PMSM with inner rotor while the second one is PMSM with outer rotor.

PMSMs are widely used because of their ability to achieve a high torque, high power density and high efficiency. Moreover, their mechanical robustness, compactness, ability of wide flux weakening and high-speed operation make them proper for electric vehicle applications. Despite the benefits of the PMSMs, they suffer from the high cost because of using magnets in their designs to provide the magnetic field [4].

PMSM is divided into two types according to the position of its rotor, which are inner rotor and outer rotor PMSMs, as illustrated in Fig. 1. The figure clearly shows that the external diameter of the motor with an outer rotor is larger than that of the motor with an inner rotor. Therefore according to equation (1), motor with an outer rotor structure can produce more torque; because the torque is directly proportional to the square value of rotor diameter. The motor copper loss occurs in stator windings, where the heat generated from. Thus in terms of heat dissipation, motor with an inner rotor can be refrigerated easier as its stator surface is directly attached to the outside. Whilean outer rotor usually needs its own coolant system.

$$T = KD^2L_{act} \qquad (1)$$

Where T is motor torque (N.m), K is a constant depends on motor parameters, D is rotor diameter (m) and L is the active length of the motor (m).



a. b.

Figure 1: PMSM rotor structures: a: inner rotor and b: outer rotor

In this section, a brief introduction has been given while section two shows a literature review about a number of researches has been done in the same field. Then section three shows the methods that were used to design the motors. In section four, the results and comparison between both proposed designs have been discussed whereas in section five the effects of motor components have been investigated.

2. LITERATURE REVIEW

Riders of electric bicycles are looking for lightness, cheapness, eco-friendly and reliable bicycles. While reviewing recent researches on bicycle's electric motor, it can be noticed that most of them are trying to make efficient, light and cheap motors to satisfy the customer needs. This study also tried to design efficient motors and it could achieve better results compared with some other reviewed papers.

In paper [5], a PMSM with inner rotor was designed and its author claims that "outer rotor PMSM motors are usually 15% lighter than the inner rotor designs". However, our paper and paper [6] found that the weight of the inner rotor motor design is lighter than the outer rotor motor design. Paper [7] discussed the design of an interior PMSM with an outer rotor type of machine for an electric bicycle application; the design achieved around 92.6% efficiency. While, paper [8] and [9] combined radial and axial flux to design a Multi Flux Permanent Magnet (MFPM) motor for electric bicycle applications, their motor efficiencies were poor compared to our presented designs, which both achieved an efficiency of more than 94%. While authors of paper [10] tried to design emerging machines that included four different types of permanent magnets which were: PM hybrid, PM Vernier (PMVB), PM magnetic-geared (PMMG) and PM memory (PMMB). Some of their machines achieved the desired torque with the assistant of a gearbox while the speed range was limited to 1000 rpm but their motors consumed high current which sometimes reached 18.5 A.

Some other researchers used cheap type of magnets to reduce the price of the motor, for example in the paper [1], authors used ferrite magnet in their design as it is cheap compared to NdFeB: Neodymium Iron Boron which was used in our design. But this kind of magnet (ferrite magnet) gives low flux, thus authors of paper [1] had to use a large amount of magnet in order to produce the required energy, which led to an increase in the size and weight of the motor. Moreover, they used an inset gearbox inside the motor to increase the torque which in our case is a drawback due to the limited space.

3. METHODS AND MATERIALS

As it has been mentioned in section one, space where the motor should be placed in the bicycle is limited. Therefore, the challenge was to design a motor that is capable to spin at the desired speed at a small size and lightweight. In this study, two types of rotor structures were designed by using Motor Solve Software which in turn based on Finite Element Analysis (FEA). The two types were interior and exterior rotors.

3.1. First design: PMSM with inner rotor

This design used inset magnets to produce flux, magnet type was NdFeB: Neodymium Iron Boron, as shown in Fig. 2. The parameters of this design were chosen quite accurately to meet the desired speed and torque with high efficiency. This type of motor with the interior rotor is suitable to fit the area between the two cranks and the chain wheel of the bicycle.

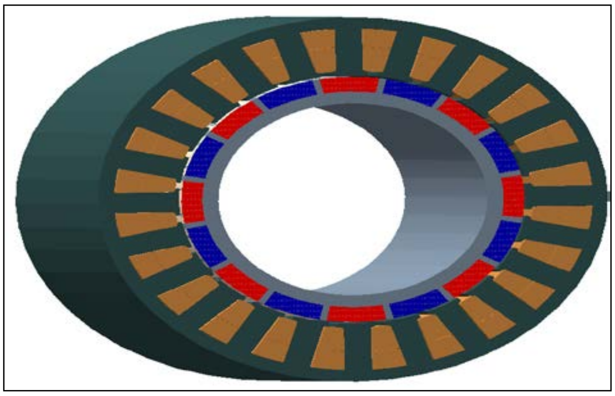


Figure 2: 3D model design of PMSM with inner rotor.

3.2. Second design: PMSM with outer rotor

Whereas, the second motor was designed to havean exterior rotor structure with surface mounted magnets. Magnet type (NdFeB: Neodymium Iron Boron), as shown in Fig. 3. It was designed to fit within the wheel, thus the rotor part of the motor was chosen to be external in order to rotate the tires of the electric bicycles.

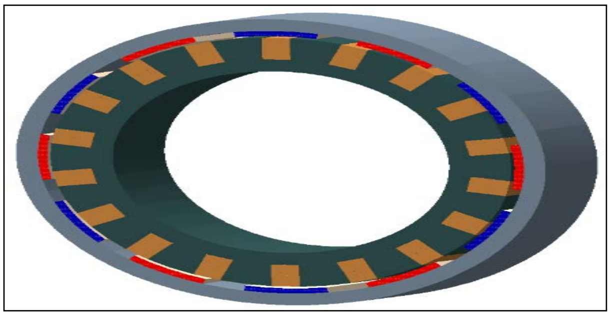


Figure 3: 3D model design of PMSM with outer rotor.

As has been discussed earlier that this paper used suitable parameters for both designs in order to run the motors more efficiently, and the purpose was to run the motors at rated speed 1143 RPM, which is equal to 20 Km/h. In addition, the rated power and the rated voltage were 250 W and 70 V respectively. Therefore, the parameters of each design, inner and outer rotor PMSMs, have been selected separately to achieve the above requirements, specifically the small size and lightweight. Table 1 shows the parameters that were used to design both motors.

Table 1: Design parameters of the proposed inner and outer rotor structures of PMSMS

Mass	Inner rotor	Outer rotor
Rotor core mass (kg)	0.240	0.877
Rotor magnets mass (kg)	0.258	0.227
Rotor sleeve mass (kg)	0	0
Stator core mass (kg)	0.993	1.46
Stator winding mass (kg)	0.355	0.495
Rotor Dimensions	**Inner rotor**	**Outer rotor**
Rotor outer diameter (mm)	74	170
Rotor inner diameter (mm)	58	150
Magnet thickness (mm)	4.5	3
Magnet angle (mm)	20	20
Number of poles (magnets)	16	12
Stack height(mm)	40	-
Stator dimensions	**Inner rotor**	**Outer rotor**
Number of slots	24	18
Number of phases	3	3
Number of turns	12.5	16
Coil fill factor	35	40
Air gap thinness(mm)	0.5	1
Stator inner diameter (mm)	75	108
Stator outer diameter(mm)	110	148
Slot depth(mm)	14	13
Slot opening width (mm)	2	9
Tooth tang angle (mm)	20	-
Tooth width (mm)	6	-
Stack length (mm)	-	32
Supply Voltage (Volt DC)	70	70
Rated Current (A)	3.52	3
Rated Speed (RPM)	1143	1143

4. RESULTS AND DISCUSION

This work, as we discussed earlier, has designed two motors of PMSM with different rotor structures. In the first motor design, the rotor was chosen to be an inner type to fit in the area between the two cranks and the chain wheel of the bicycle. While in the second motor design, the rotor was chosen to be an external type to fit within the wheel. Meanwhile, the challenge is the lack of space where the motor should be fitted into.

The comparison between the two proposed motor designs was regarding the motor volume, mass, cost and efficiency, as shown in Table 2. From the Motor Solve simulation results, it can be noticed that the first motor could run at rated speed with a reasonable torque as shown in Fig. 4. In terms of motor flux, the flux density distribution of the first design was quite satisfying with an average distribution varies between 0.6 to 1.5 wb, as demonstrated in Fig 5. In addition, the motor with internal rotor was rotating at a high efficiency as shown in Fig. 6. In terms of costs of the motors, this research estimated the cost by calculating the price in $ per Kg of each motor element individually, which are given in Table 1; including copper, steel and magnet. Then the total cost was obtained by mixing all costs of those individual elements. Bearing in mind that such calculations of cost could vary between time to time depending on the market. The results showed that the efficiencies and costs of both designs were so close but the difference was in weight and size. The volume of both designs was calculated by using equation (2, 3 and 4) based on the parameters shown in Table 1. The mass was also calculated according to the mass parameters given in Table 1 that belongs to the proposed designs.

$$Volume = \pi\, r^2 h \tag{2}$$

$$h = l + 2(height\ of\ end\ winding) + 2(house\ thickness) \tag{3}$$

$$r = house\ thickness + \frac{diameter\ of\ the\ machine}{2} \tag{4}$$

Where r is radius of outer diameter (m) and l is axial (stack) length (m).The motor was assumed cylindrical. Another calculation for volume can be made using the density, as given below:

$$Volume\ = mass/density \tag{5}$$

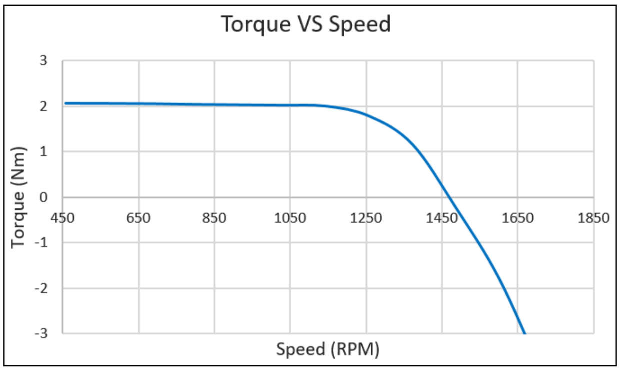


Figure 4: Torque-Speed characteristics of inner rotor PMSM.

Magnet price is the most expensive part in machines. In this work, the first motor is designed using 16 poles with 4.5 mm thickness, while the second motor is designed using 12 poles with 3 mm thickness. Therefore the price of the second motor is slightly lower than the price of the first motor.

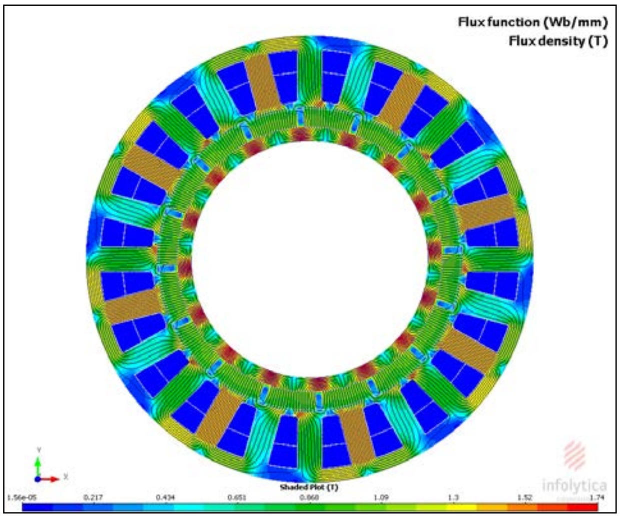


Figure 5: Flux density distribution of inner rotor PMSM.

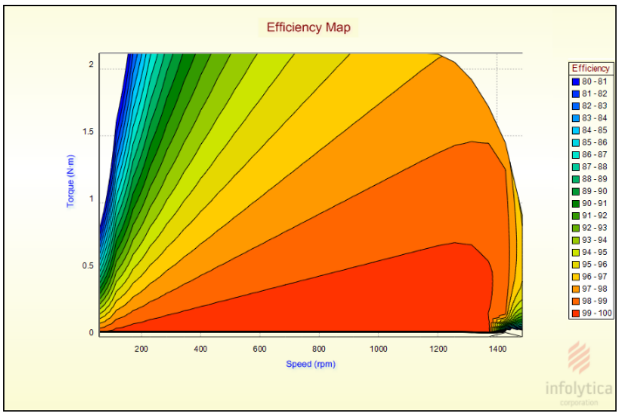


Figure 6: Efficiency map of inner rotor PMSM.

The performance of the second design was also satisfying as it rotated at an efficiency exceeding 95%, as represented in Fig. 7. Moreover, the desired speed was achieved at the outer rotor with high torque as shown in torque-speed characteristics (Fig. 8). While Fig. 9 shows the flux density distribution of the outer rotor PMSM. It can be seen from results of both motors that the flux distributed uniformly inside the core of the motors. Therefore, the rotations of the motors were quite satisfactory.

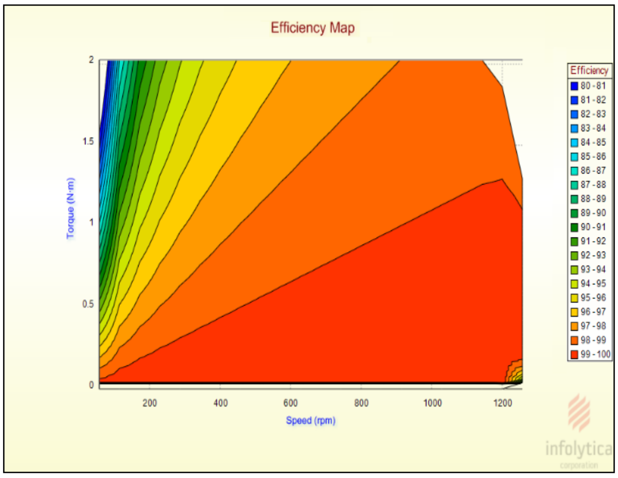


Figure 7: Efficiency map of outer rotor PMSM.

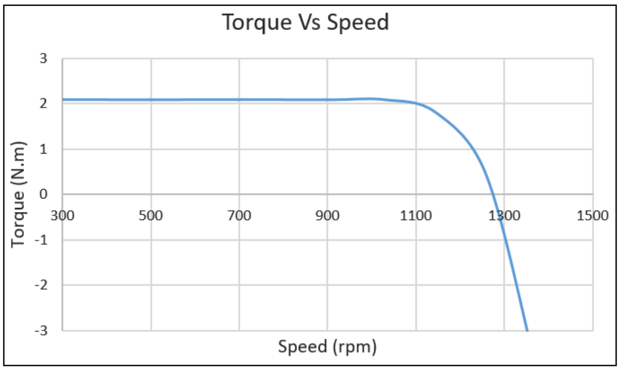


Figure 8: Torque-Speed characteristics of outer rotor PMSM.

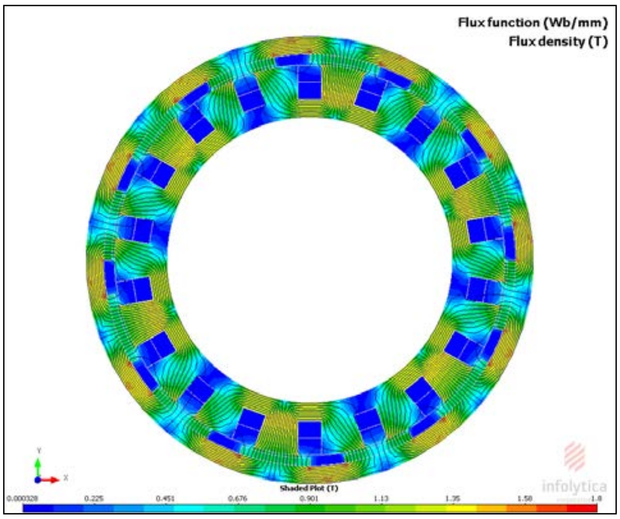


Figure 9: Flux density distribution of outer rotor PMSM.

Table 2 presents a comparison between the two rotor structure motor designs. The result shows that the two motors were run efficiently with low cost. However, the torque of the motor with an outer rotor was slightly more than the torque of the inner rotor type of motor.

Table 2: Comparison of PMSM with inner and outer rotor.

	Inner rotor design	**Outer rotor design**
Motor Volume (mm^3)	639205.82	1240297.31
Motor Mass (Kg)	1.846	3.059
Motor Cost ($)	29.31	28.53
Motor Efficiency (%)	94-100	96-100

5. THE EFFECTS OF MOTOR PARAMETERS

This work also investigated the effects of motor parameters on the motor performance. The second design, which is PMSM with outer rotor was chosen as an example for this purpose. The following parameters were changed in order to investigate their effects:

5.1. Current effect

The current was increased by 50% to check its effect on motor performance. After increasing current, the flux linkage will increase as a result the motor torque increased as it is directly proportional to flux linkage according to the following formula:

$$T = \frac{3}{2} * \frac{P}{2} * \Psi_{iqs} \quad (6)$$

$$T = \frac{60\, P}{2\pi\, N} \quad (7)$$

Where P is the number of pole pairs and Ψ_{iqs} is stator flux linkage (wb), which is directly proportional to the stator current.

From Fig. 10, it can be seen that the speed decrease slightly with increasing current as it is inversely proportional to motor torque according to equation (7),

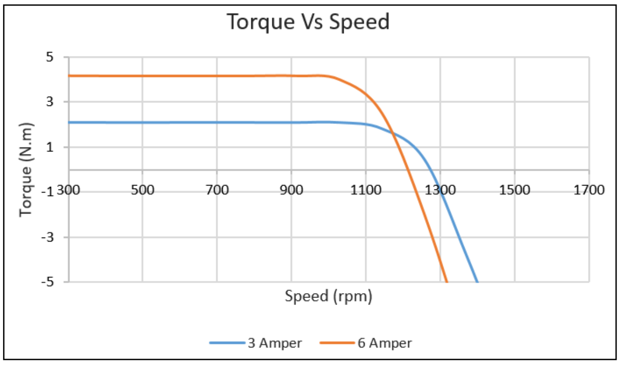


Figure 10: Torque-Speed characteristics of outer rotor PMSM with different current values

5.2. Advanced angle effect (Field weakening)

When the motor reaches the base speed at the rated source voltage 70 volt, the current regulator reaches its saturation [11]. Therefore, to attain further acceleration, field-weakening control is necessary [12]. Through increasing the advanced angle (Θ) which is an angle between quadrature axis of the motor and the current, an increase in the speed range can be noticed. This angle affects the performance of the motor because any increase in advance angle will achieve a maximum torque at a higher speed [13]. Fig. 12 shows the effect of the field weakening, which increased speed after increasing angle from 0 to 10.

The q-axis and d-axis components, those are shown in Fig. 11 ($I_{d\ new}$,$I_{q\ new}$), are calculated according to adjusted phase angle. When increasing the angle Θ, the d-axis current will increase while q-axis current will decrease, and therefore, the system switches to field-weakening mode [11] [13]. Fig. 11 describes the process clearly.

$$I_{d\ new} = I_{new} \sin\theta_2 \quad (8)$$

$$I_{q\ new} = I_{new} \cos\theta_2 \quad (9)$$

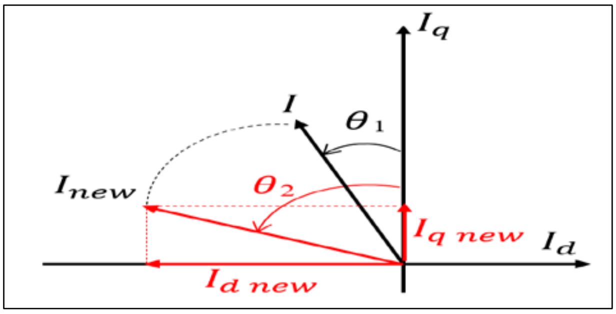


Figure 11: Advanced angle

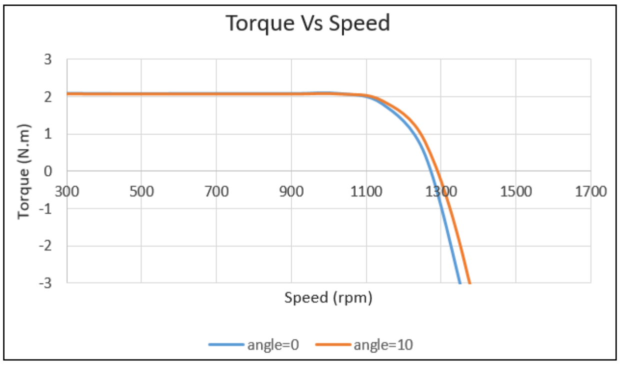


Figure 12: Torque-Speed characteristics of outer rotor PMSM with different advanced angles

5.3. Stack length effect

According to equation (10), stack length has a direct impacton machine torque. Thus after increasing stack length the motor torque increased; while motor speed decreased distinctly, as shown in Fig. 13.

$$T = B_g * I_g * l * r \quad (10)$$

Where $T$is the torque per meter, B_g is the air-gap flux density and $I_g$is instantaneous current.

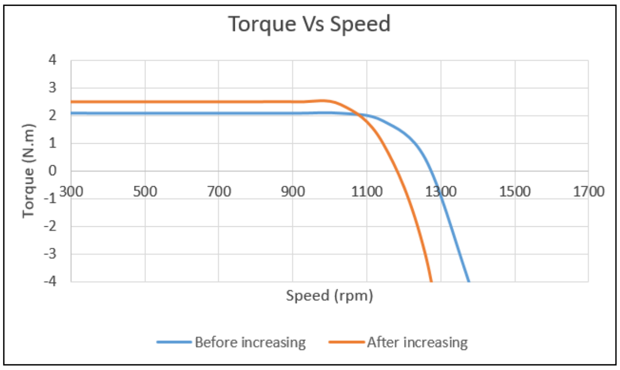


Figure 13: Torque-Speed characteristics of outer rotor PMSM with different stack length.

5.4. External diameter effect

External diameter has a significant influence on PMSM performance because all parameters inside motor will change while changing external diameter. This paper investigated the effect of external diameter on motor torque and speed after changing its value from 32 mm to 42 mm, as shown in Fig. 14. As a result, the torque increased with increasing diameter because torque is directly proportional to the rotor radius. However, the speed decreased as it is inversely changes with torque.

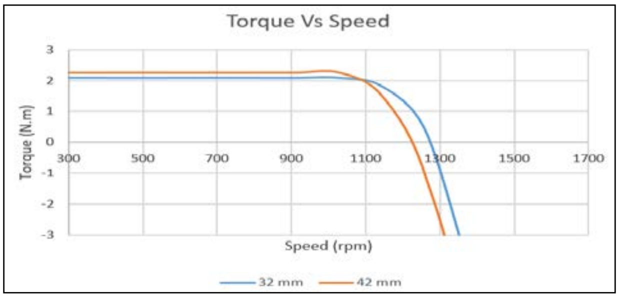


Figure 14: Torque-Speed characteristics of outer rotor PMSM with different external diameters

6. CONCLUSION

This paper proposed two designs of PMSMs with different rotor types, which were inner and outer rotors, which in turn will be used to rotate wheels in an electrical bicycle. In addition, this paper presented a comparison between both proposed motors to choose a proper one. The comparison was based on four criteria, which were: size, weight, efficiency, and price (Table 2). The presented designs showed that both motors have high efficiency and low price, while the differences were in size and weight. The first motor design, that has an inner rotor, achieved the desired speed and torque at a lower weight and smaller size than the second design which has an outer rotor. The result that this study has reached is that the size of the motor and its weight are important due to the lack of enough space, beside the negative effect of high weight on the bicycle and its pedals. Therefore, a PMSM with inner rotor is best suited for electric bicycle applications. Finally, this paper investigated the effects of some major motor components, such as stack length, external diameter, advance angle and supply current. Results show that any increase in these components will increase torque and decrease speed except advance angle, which slightly increases speed only.

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