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# Design Comparison of Inner and Outer Rotor of Permanent Magnet Flux Switching Machine for Electric Bicycle Application

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**Abstract**—Recent advancements have led to the development of flux switching machines (FSMs) with flux sources within the stators. The advantage of being a single-piece machine with a robust rotor structure makes FSM an excellent choice for speed applications. There are three categories of FSM, namely, the permanent magnet (PM) FSM, the field excitation (FE) FSM, and the hybrid excitation (HE) FSM. The PMFSM and the FEFSM have their respective PM and field excitation coil (FEC) as their key flux sources. Meanwhile, as the name suggests, the HEFSM has a combination of PM and FECs as the flux sources. The PMFSM is a simple and cheap machine, and it has the ability to control variable flux, which would be suitable for an electric bicycle. Thus, this paper will present a design comparison between an inner rotor and an outer rotor for a single-phase permanent magnet flux switching machine with 8S-10P, designed specifically for an electric bicycle. The performance of this machine was validated using the 2D-FEA. As conclusion, the outer-rotor has much higher torque approximately at 54.2% of an inner-rotor PMFSM. From the comprehensive analysis of both designs it can be conclude that output performance is lower than the SRM and IPMSM design machine. But, it shows that the possibility to increase the design performance by using “deterministic optimization method”.

## 1. Introduction

Conventional vehicles for personal mobility have over the years been operating by means of internal combustion engine (i.e., ICE) which is based on fossil fuels. In addition, an over whelming increase in demand for private vehicles has recently been observed in line with an equal increase in populations on a global scale. In such a scenario, ICE automobile is seen as a potential solution for many urban dwellers, by and large. Not with standing, three problems are associated with ICE namely environmental, economic and political problems. With regards to the environmental issues, one of the major ones is the emissions. Specifically, the problem of air pollution at an increased level due to the harmful emissions released by hydrocarbon fuelled power sources has been a long-standing issue [1][2].

In addition, the perceived lower efficiency of the use of fossil fuel is another setback of the ICE automobile. In recent years, some concerted efforts have been undertaken by various parties within the automotive industry to address the dependency on fossil fuels and to reduce the greenhouse gases emitted per km of travel [3]. In their attempts to address these issues, auto-manufacturers have now shifted towards new technologies such as electric vehicles (EVs) and hybrid electric vehicles (HEVs). Notably, the idea of operating EV as an alternative can be traced back to the early stages of the automotive industry. Since the year of 1910, a steady increase has been observed in the number of EVs compared to the vehicles with ICE. Some scholars have asserted that the concerns raised by various parties in relation to the amount of pollutants released into the atmosphere each day by ICE have made the Evs to come to the fore. They are now said to be the future of transportation. Upon comprehensively reviewing the literature, it was found that electric vehicles mostly refer to cars which operate electronically [22-23].

Notably, another type of electric which sometimes go unnoticed is the electric bicycle. It is noteworthy that the electric bicycles have over the years been gaining an increased due to their lower energy cost and environmental friendliness [4]. One of the reasons cited for the popularity of the electric bicycle is that it has the edge of relatively higher energy efficiency over the other energy forms. Hence, a significant number of individuals these days opt for an electric bicycle rather than an electric car or an electric motorcycle [5]. It is worth highlighting that studies which have looked into the electronically operating vehicles are scarce.

The motor which operates the bicycle is the most important component which requires meticulous attention in the course of designing the bicycle. The type and the performance characteristics of the electric motor equipped in the bicycles may have significant consequences on the overall performance of the Electric Bicycle [6]. Among the types of electric motors equipped with bicycles are inter alia, Multi-Flux Permanent Magnet (MFPM), Switch Reluctance Motor (SRM) and a Permanent Magnet Synchronous Machines (PMSMs) [7-9]. Even though many of its features are appealing, it is not exempt from some limitations such as lower power, lower torque, higher volume of permanent magnet (PM), and the level of noise which is not desirable in this application. Considering the significance of these vehicles in societies around the world, more studies need to be carried out to address the issues of electric machines with reduced amount of PM, reasonable price range, easy to design, higher power and torque performance and higher efficiency. It should be noted that PMFSM has notably been an interesting research topic because of its higher power density and robust rotor structure [12], [13].

This current study has conducted a design comparison between an inner rotor and an outer rotor for a single-phase 8Slot-12Pole PMFSM, as shown in Figure 1. The figure shows that each PMFSM has 8 pieces of PM, and 12 rotor poles, with the armature coil within the stator. Meanwhile, the rotor was constructed from a single piece of iron, which was more robust and appropriate for electric vehicles. Table 1 lists the design restrictions and target specifications for the application of PMFSM in electric bicycles.

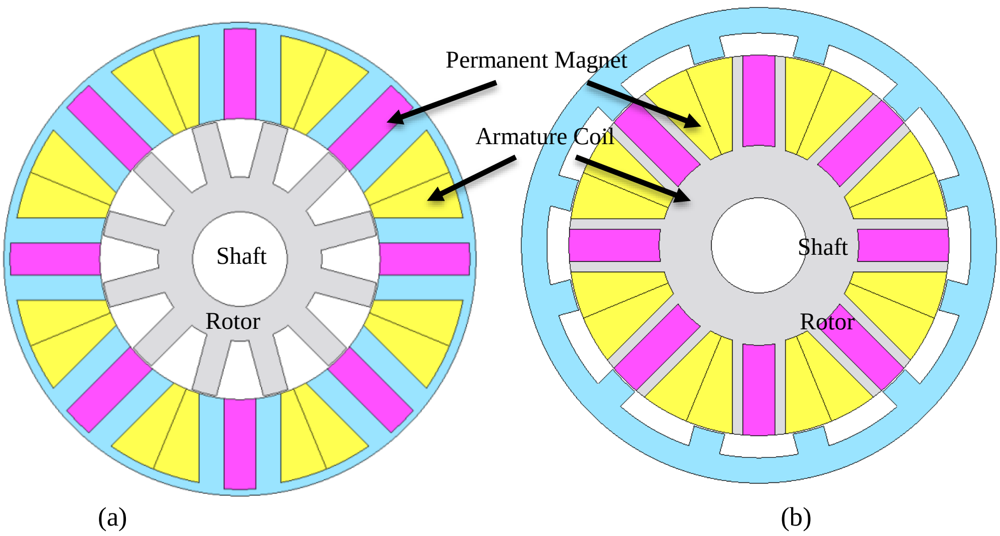


Fig. 1 Initial design of PMFSMs (a) Inner rotor (b) Outer rotor

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Table 1 PMFSM Design Restriction and Specification for Electric Bicycle Application

| | **Items** | **Unit** | **IPMSM** | **SRM** | **PMFSM** |
|---|---|---|---|---|---|
| Geometrical dimension and volume | Number of Slot Pole | - | 20S-18P | 6S-10P | 8S-12P |
| | Number of phase | - | 5 | 3 | 1 |
| | Size of Motor | mm | 190 | 220 | 75 |
| | PM Weight | g | 431 | - | <100 |
| Input voltage and current | Maximum DC Bus Voltage | V | <40 | 48 | 36 |
| | Inverter Maximum Current | A | 6 | 35 | 10.60 |
| Output Performance | Maximum Power Density | W/m $m^3$ | 300 | 531 | 500 |
| | Maximum Torque Density | Nm | 11 | 9.5 | >11 |
| | Motor Weight | Kg | 6.804 | 6.7 | <1 |

## 2. Finite Element Analysis

Initially, the rotor, stator, permanent magnet and armature coil of the proposed design are drawn by using Geometry Editor by JMAG-Designer ver. 14.0, released by the Japan Research Institute (JRI) in order to carry out the analytical study which is completed by 2D-Finite Element Analysis (FEA). The design specifications and limitations of the proposed machine are listed in Table 1.

Table 2 The Proposed Inner And Outer Rotor PMFSM Initial Design Parameters

| Parameter | INNER ROTOR | OUTER ROTOR |
|---|---|---|
| No. of phase | 1 | 1 |
| Number of stator pole | 8 | 8 |
| Number of rotor pole | 12 | 12 |
| Stator inner radius(mm) | 22.25 | 7.5 |
| Stator outer radius(mm) | 37.5 | 30 |
| Rotor outer radius(mm) | 22 | 37.5 |
| Rotor inner radius(mm) | 7.5 | 30.25 |
| Rotor tooth width(mm) | 4 | 5 |
| Stator tooth width(mm) | 4 | 1.6 |
| Stator pole height(mm) | 15.25 | 14.25 |
| Rotor pole height(mm) | 9 | 3.25 |
| Motor stack length(mm) | 20.3 | 20.3 |
| Air gap length (mm) | 0.25 | 0.25 |
| PM Volume (g) | 87 | 87 |

This study used the commercial FEA package (JMAG-Designer, ver. 14.0), as the 2D-FEA solver, which was released by the Japan Research Institute (JRI). The rotor, the stator, the armature coil, and the PMs were drawn using the JMAG Editor. Next, the materials, the conditions, the circuits, and the properties of this motor were keyed into the JMAG Designer. Figure 2 shows the process designing and setting the conditions for these motors. Additionally, the coil arrangements were analysed to confirm the operating principle of both PMFSMs as well as to determine the position of each armature coil phase. This was followed by comparing the flux linkages at the armature current densities, the Ja flux linkages, the distribution of flux at zero rotor position, and the induced voltages. The final step was to analyse the power and torque at various Ja of both rotors.

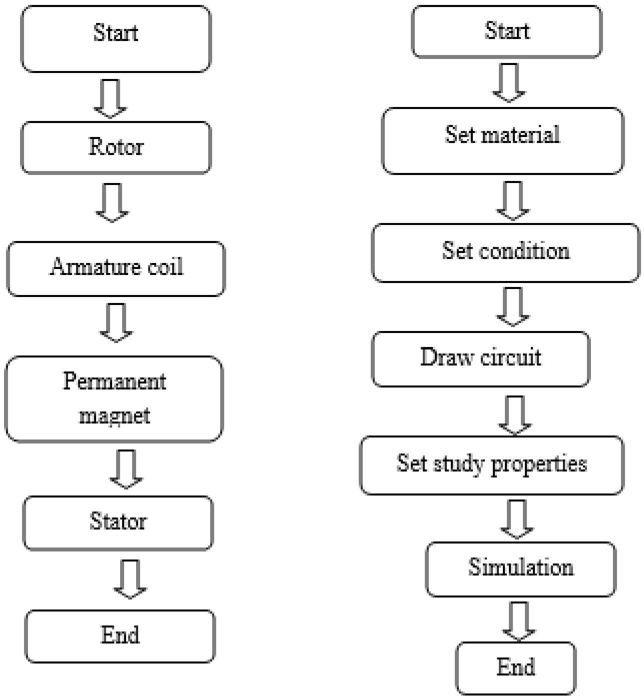


Fig. 2. Design methodology of the proposed PMFSMs
(a) Drawing (b) Conditions setting

### 3. Performance of the proposed PMFSMS based on 2D-FEA

NEOMAX-35AH was used as the PM, while the 35A210 electromagnetic steel became the rotor and the stator core. Equation (1) was used to calculate the area of armature coil (Sa) that would produce an optimum number of turns (Na). The armature current density (Ja) was set at 10 Arms/mm2. This study applied 136 turns of the armature coil, and 87 g of PMs was used.

$$N_a = \frac{J_a \alpha S_a}{I_a} \tag{1}$$

The stack length of 20.3 mm was set during the full model conversion.This proposed motor has a rotation of 1/Nr of a revolution, while the flux linkage of the armature has one periodic cycle. Therefore, the frequency of the back-emf, which was induced in the armature coil, was Nr times of the mechanical rotational frequency. Equation 2 shows the relationship between the mechanical rotation frequency (fm) and the electrical frequency (fe) of this motor. Meanwhile, Equation 3 can be used to determine the end time (T).

$$f_e = N_r f_m \tag{2}$$

$$T = \frac{1}{f_e} \tag{3}$$

3.1. Result performance of flux linkage, cogging torque and back-emf analysis

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The performances of the proposed inner and outer rotors, which include the flux linkage, cogging torque and back-emf, were analysed in an open circuit. The flux linkage analysis was conducted to confirm that the magnetic flux generated by the PMs was in the same phase. Figure 3 shows the flux linkages for PMFSMs with inner and outer rotors.

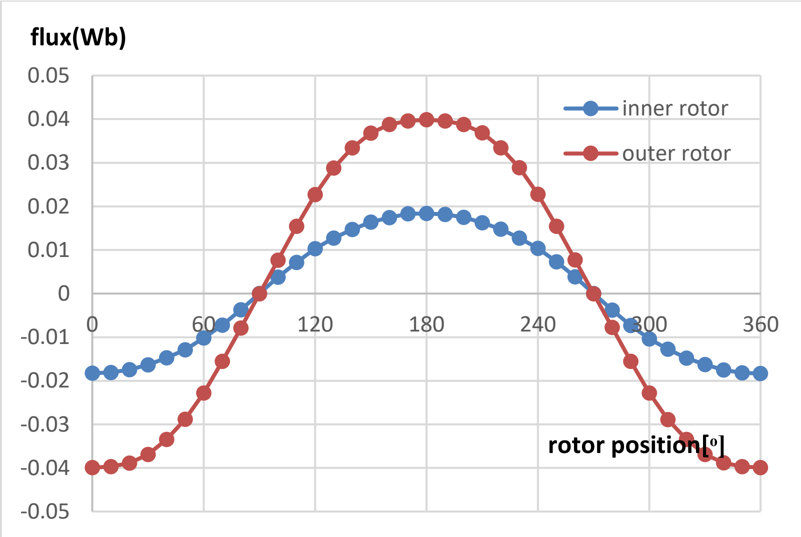


Fig. 3. Finite-element-predicted of phase flux linkage at inner rotor and outer rotor of PMFSM

As an example, the lowest amplitude of magnetic flux generated is when the proposed machine is set at empty PM and maximum current density, Ja of 10 A/mm2. From Figure. 4, it is clearly that at open circuit test, the magnetic flux linkage in all conditions is in the same phase with essential sinusoidal waveform and outer rotor of PMFSM come out with the highest flux linkage compare to inner rotor of PMFSM with 0.04Wb. Further investigation on this phenomenon is described in load test condition.

Back EMF is commonly used to refer to the voltage that occurs in electric motors where there is relative motion between the armature of the motor and the magnetic field from the motor's field magnets, or windings. Figure 4 shown that waveform for inner-rotor and outer-rotor exhibits a more favorable sinusoidal feature with amplitude of approximately 13.6V and 28V respectively. Main factors influencing the back EMF is magnetic-pole eccentricity, the slot opening, the thickness of PM and the equivalent length of air gap.

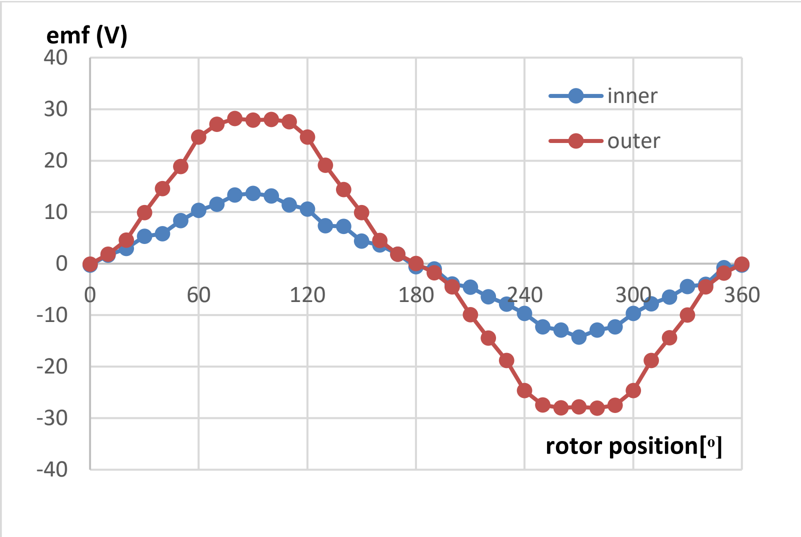


Fig. 4. Back-emf at 500 r/min

The cogging torque analyses for PMFSM machine types were diagnosed by setting armature current density, Ja=0 Arms/mm2. Figure 5 shows the cogging torque investigation of the examined 8Slot-12Pole PMFSM for inner-rotor and outer-rotor design machines. This figure shows that the initial outer rotor had produced higher cogging torque compared to the outer rotor of the PMFSMs. The peak-to-peak cogging torque of this motor was roughly 4.64 Nm, while the cogging torque of the inner rotor of the PMFSM was 3.82 Nm. Based on the previous study, cogging torque can be relatively reduced by varying the air gap distance between stator and rotor [14]. In fact, cogging torque could be further decrease by rotor pole-notching, rotor pole-pairing and rotor skewing.

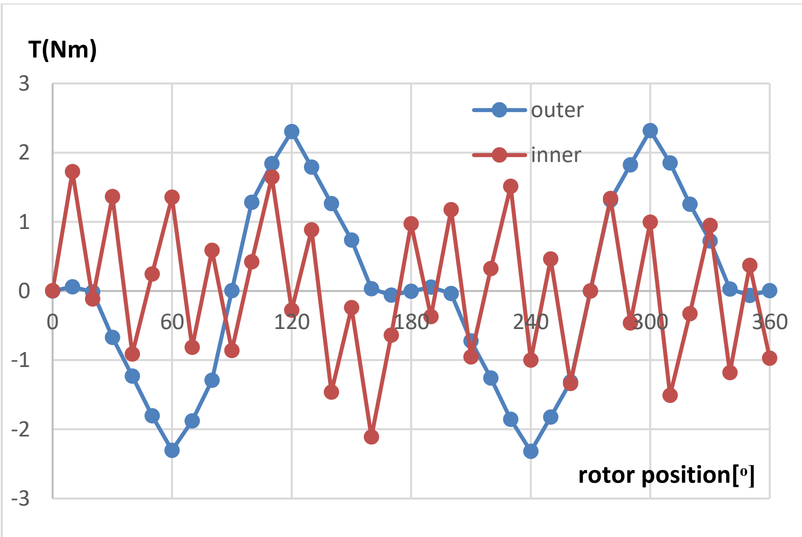


Fig. 5. Cogging torque of the proposed PMFSM

## 3.2 Initial Torque and Power Performance

Under this load analysis discussion, the current density of armature coil, Ja is being supplied into the system varied from Ja of 5 Arms/mm$^2$ up to JA of 30 Arms/mm$^2$. In order to accomplish this procedure, the number of turn of armature coil are calculated and set by using Equation 4.

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$$I_a = \frac{J_a \alpha_a S_a}{N_a} \tag{4}$$

It is noteworthy that the calculation of output power can be performed by means of manipulating the data of both torque and speed. Since all the required data were obtained in the previous analysis, equation (7) was therefore used to substitute them. Subsequently, as for the rotation on a fixed axis, the calculated power was observed to be equal to the multiplication between torque and angular velocity of the rotating piece, which was defined by Equations (5), (6), and (7) respectively.

$$P = \tau\omega \tag{5}$$

$$\omega = \frac{2\pi S}{60} \tag{6}$$

$$P = \tau\left(\frac{2\pi S}{60}\right) \tag{7}$$

Where P is power in kilowatt (kW), τ is torque in Newton meter (Nm), and S is speed in revolution per minute (r/min). Therefore, the drive performances of the initial design machine in terms of torque and power versus Ja at inner rotor and outer rotor position is shown in Fig. 6 and Fig. 7 respectively. From the Fig. 6, it can be seen from the graph, that the output torque is directly proportional to armature current densities. The maximum torque inner-rotor at Ja of 10 Arms/mm2, is obtained at 0.38 Nm. Hence, the maximum torque for outer-rotor at Ja of 10 Arms/mm2, is obtained at 0.8 Nm.

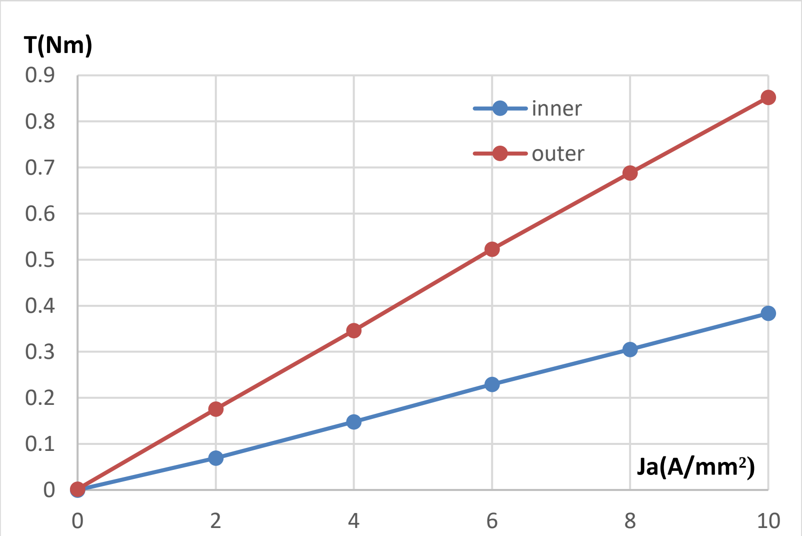

Fig. 6. Torque versus Ja at inner and outer rotor of PMFSM

Figure 7 shows the power versus Ja of the inner and outer rotors. The power is straight forwardly correlated with the armature current densities (Ja) at 10 Arms/mm². The figure shows that the inner rotor has a maximum power of 436 W. Meanwhile, the maximum power of the outer rotor was 416 W.

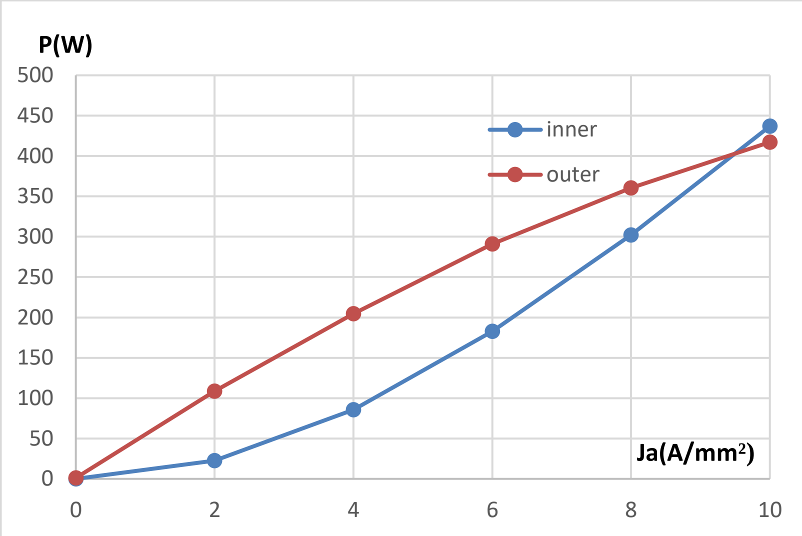


Fig. 7. Torque versus Ja at inner and outer rotor of PMFSM

## 4. Conclusion

Design and performance comparison of 8S-12P with an inner and an outer rotor PMFSMs have been proposed and investigated in this paper. The proposed machine has small size of motor compared to the IPMSM and SRM motor and it can be anticipated as very cost-effective machine. As conclusion, the outer-rotor has much higher torque approximately at 54.2% of an inner- rotor PMFSM. From the comprehensive analysis of both designs it can be conclude that output performance is lower than the SRM and IPMSM design machine. But, it shows that the possibility to increase the design performance by using “deterministic optimization method”.

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