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Design and Performance of 8Slot-12Pole Permanent Magnet Flux Switching Machines for Electric Bicycle Application

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ABSTRACT

This paper presents a new design and performance of single phase permanent magnet flux-switching machine (PMFSM) for electric bicycle application. 8Slot-12Pole design machine were choose by analyzing the highest power density value. All active parts such as permanent magnet and armature coil are located on the stator, while the rotor part consists of only single piece iron. PMFSM have a great advantage with robust rotor structure that make it much higher power and applicable for EV application compared to SRM and IPMSM. The design, operating principles, characteristics of torque, and power of this new topology are investigated by JMAG-Designer via a 2D-FEA. Size of motor and volume of PM is designed at 75mm and 80g, respectively. Based on the investigation, it can be concluded that the proposed topology of single phase 8Slot 12Pole PMFSM achieved the target of highest performance of power density, approximately at 0.113W/mm3 with reduced permanent magnet and size of design motor. Due to the low torque performance of this initial design, further works is ongoing to improve the torque performance. In future work, outer rotor PMFSM structure design will be presented and compared with the "Deterministic Optimization Method" to improve the initial design.

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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. Notwithstanding, 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.

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 increaseddue to their lower energy cost and environmental friendliness [4]. One of the reasons cited for the popularity of the electric bicycle is thatit has the edge ofrelatively higher energy efficiency overthe other energy forms. Hence, a significant number of individuals these days opt foran 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].

2. OPERATING PRINCIPLE ON INITIAL DESIGN OF 8S-12P PMFSM

Permanent Magnet Flux Switching Motors can be potentially applied in electric bicycle which are design to reduce the size of design motor structure and volume of permanent magnet. As one alternative to overcome this problem, a new structure of single phase 8Slot-12Pole permanent magnet flux switching machine is proposed as shown in Figure 1. From the design in Figure 1, it is clear that the machine consists of only permanent magnet and armature coil allocated on the stator part. The rotor consists of only a single piece iron, becoming more robust and suitable for electric vehicle application.

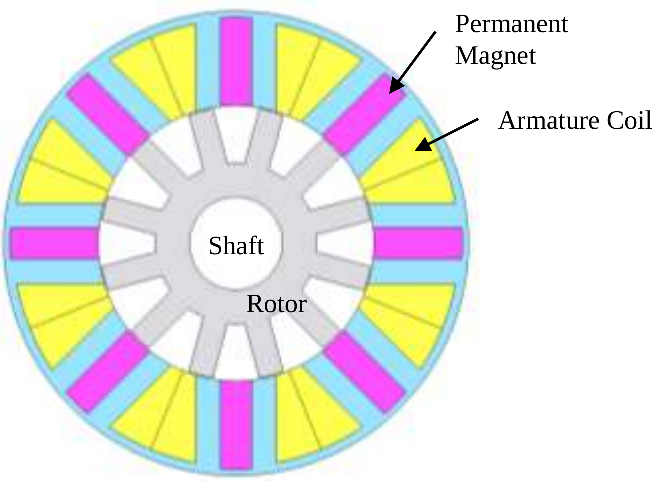

Figure 1. Initial design of 8Slot-12Pole PMFSM

2.1. 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 1. Design Restriction and Specification

Parameter	8S-10P PMFSM
No. of phase	1
Number of stator pole	8
Number of rotor pole	12
Stator inner radius(mm)	22.25
Stator outer radius(mm)	37.5
Rotor outer radius(mm)	22
Rotor inner radius(mm)	7.5
Rotor tooth width(mm)	4
Stator tooth width(mm)	4
Stator pole height(mm)	15.25
Rotor pole height(mm)	9
Motor stack length(mm)	20.3
Air gap length (mm)	0.25
PM Volume (g)	80

Necessary steps involved in the process, the expected end time and division were set in the step control components where as the stack length was spelt outinthe full model conversion. In this regard, the steps, division and the stack length wereset to 37, 36 and 20.3mm, respectively.In this proposed motor, the motor rotation is through $1/N_r$ of a revolution, the flux linkage of armature containsone periodic cycle and therefore, the frequency of back-emf induced in the armature coil is N_r times of the mechanical rotational frequency. In general, the mechanical rotation frequency, f_m and the electrical frequency, f_e for the proposed machine can be spelt outby means of Equation 1 and for the expected end time, T is calculated by means of Equation 2.

$$f_e = N_r f_m \tag{1}$$

$$T = \frac{1}{f_e} \tag{2}$$

The where f_e, N_r and f_m refer to the electrical frequency, number of rotor poles and mechanical rotation frequency, respectively. The value with in the armature coil and number of turns are recorded correctly by means of Equation 4 and 5, respectively

$$N_a = \frac{J_a \alpha S_a}{I_a} \tag{3}$$

$$N_a = \frac{\alpha S_a}{A_{copper}} \tag{4}$$

Where *N, J, α, S* and *I* refer to thenumber of turns, current density, filling factor, slot area and input current, respectively. For the subscript *a*represents armature coil. Referring to Table 1, the comparative performance of the electric bicycle application it can be clearly seen.

3. PERFORMANCE ANALYSIS OF NUMBER OF TURN AND FILLET ROTOR DESIGN

It has to be highlighted that the investigation of flux profiles were carried out under the open circuit conditions as can be seen in Figure 2 (a) and (b) respectively, in which the machine topology was analyzed at zero degree rotor position. As it can be observed, the machine which surfaced almost identically excited the PM flux lines and distributions in a uniform manner as the flux surged from the stator to rotor and returned passing through the rotor teeth in completing the full flux cycle of the PM. The observations also indicated that the rotor structure showed higher flux concentration at 8 out of its 12 poles, hence causing the rotor toeasily rotate even at a relatively lower supply of excited armature flux. In addition, the flux distribution was investigated with the aim of monitoring the field saturation effect on the machine it can be seen in Figure 2 (b). Not withstanding, the maximum flux density at this point was read at 2.3T.

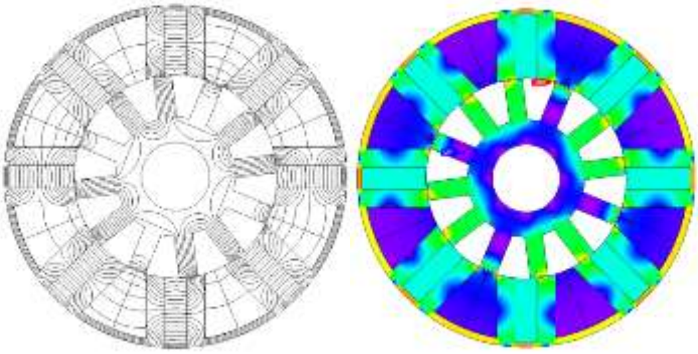

Figure 2. Flux lines and Flux Distribution of 8S-12P PMFSM

3.1. Back emf and Cogging Torque Analysis

The cogging torque analyses for PMFSM machine types were diagnosed by setting armature current density, Ja=0 Arms/mm^2. Figure 3 shows the cogging torque investigation of the examined 8Slot-12Pole PMFSM design machines, with having the highest peak-to-peak cogging torque at approximately 0.11Nm. 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. Back EMF iscommonly 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 3 shown that waveform exhibits a more favorable sinusoidal feature with amplitude of approximately 9.4V. Main factors influencing the back EMF is magnetic-pole eccentricity, the slot opening, the thickness of PM and the equivalent length of air gap.

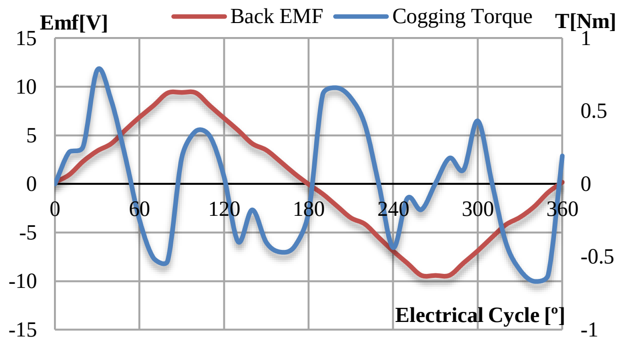

Figure 3. Cogging torque performance for 10S-15P, 8S-12P, 4S-8P and 2S-8P

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 6.

$$I_a = \frac{J_a \alpha_a S_a}{N_a} \quad (5)$$

It is note worthy that the calculation of output power can be performedby means of manipulating the data of both torque and speed. Since all the required data were obtained in the previous analysis, equation (8) 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 (6), (7), and (8) respectively.

$$P = \tau\omega \quad (6)$$

$$\omega = \frac{2\pi S}{60} \quad (7)$$

$$P = \tau\left(\frac{2\pi S}{60}\right) \quad (8)$$

Where P is power in kilowatt (kW), τ is torque in Newton metre (Nm), and S is speed in revolution per minute (r/min). Therefore, the resulting data of initial torque and power performances single phase 8S-12P PMFSM design machine are plotted in Figure 4.

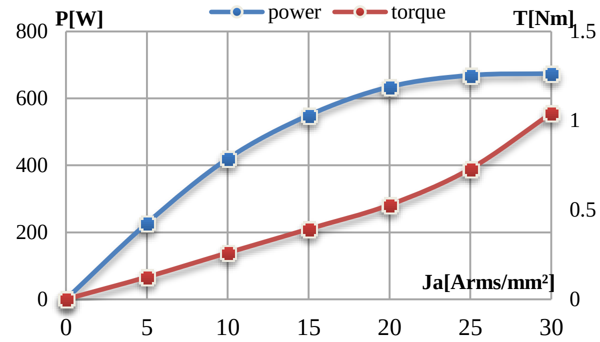

Figure 4. Ouput power versus armature current densities, Ja

Figure 4 illustrates the output torque and power waveforms obtained based on FEA at maximum current density approximately at 1.04Nm and 674W respectively. This is a great advantage of PMFSM with robust rotor structure that make it much higher power and applicable for EV application compare to IPMSM and SRM.

3.3. Torque and Power versus Speed Characteristics

Consequently, the torque and power versus speed characteristics of the designed motor is plotted in Figure 5. From the graph, the highest output torque is measured at 1.04Nm at the base speed of 6182 r/min equivalent to 14.1Km/h. On the other hand, the power curve of the proposed machine shown approximately at 542W at the same based speed of 6182 r/min. Table 2 clearly showed the comparison performance of the electric bicycle application.

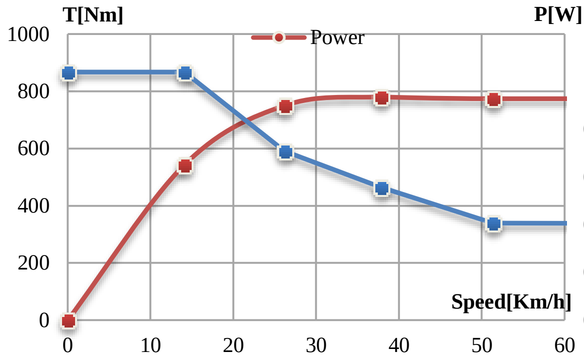

Figure 5. Torque and power vesus speed characteristic

Table 2. The Performance Comparison

Output Performance	Unit	IPMSM	SRM	PMFSM
Maximum Torque	Nm	1.6	7.05	1.04
Maximum speed	rpm	N/A	500	6812
Power Density	W/mm^3	0.009	N/A	0.113
Motor weight	Kg	6.804	6.7	921g

4. CONCLUSION

Based on the investigation carried out in the earlier section, it can be concluded that the proposed topology of single phase 8Slot 12Pole PMFSM achieved the target of high power density performance with reduced permanent magnet and size of design motor. At the same time, this design already achieved the target to reducing cost as the main objective of many electric bicycle manufactures. Due to the low torque performance of this initial design, further works is ongoing to improve the torque performance. In future work, accurate investigation for iron loss distribution should be employed and outer rotor structure design will be presented and compared with the "deterministic optimization method".

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