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H-Configuration Modular Rotor PMFSM for Passenger Drone

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Abstract : Currently, Brushless DC (BLDC) outer rotor permanent magnet motor has been applied in courier drone. This structure makes the motor less robust at high speed as well as mechanically weak. To resolve the issue, an optimization of double stator with H-design modular rotor permanent magnet PMFSM with unique features of non-overlap winding, low copper losses, high efficiency, a smaller number of permanent magnet (PM) has been proposed. The optimization based on Local Optimization Method (LOM) has been used. The project aims to ensure that the passenger drone motor designed able to show the improvement on high torque and better performances motor. In addition, the methodology of this study has been carried out in detail in order to complete and simplify the process of data collection in a more structured and ordered method by using JMAG-Designer version 16.0 software. Hence,the results for this design have been observed under no-load and load condition which shows that it is suitable with the passenger drone with modular rotor motor torque which is 46.13 Nm.
Keywords: Passenger Drone, Modular Rotor, PMFSM

1. Introduction

Poor air quality exacerbates respiratory illnesses such as asthma and bronchitis, raises the risk of life-threatening diseases such as cancer, and cost our health-care medical system with a lot of money. Basically, vehicles that use petrol and diesel as their primary fuel have serious impact on the environment, including air pollution and global warming that caused rise of temperature of the earth due to the released of carbon monoxide while operating [1]. Moreover, the rise of temperature also come from industry and electricity production at generation station and finally it can lead to natural disaster. So, air pollutant and global warming is a crucial issue to discuss in order to prevent climate change that is detrimental to human health [2].

Electric vehicles are well known in the world in order to reduce the air pollution and global warming problem. Passenger drone is one of electric vehicle that widely use nowadays. In 2016, Ehang was the first commercially company that produced drone which capable of carrying a human was introduced at the Consumer Electronics Show [3]. Obviously, permanent magnet machines have been used in electric

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vehicle technology and performance has greatly improved in less heat loss, less use of energy, increased precision and torque effectiveness for various applications [4]. Electric motors are the most important element of the Electric Vehicles (EV) motor drive system [5, 6]. In recent years, several commercial developers have conducted short crewed flights on experimental electric multi-rotor craft. Moreover, passenger drone is type of personal air vehicle that used to transport merchandise.

Considering the growing interest in Double stator PMFSM research and development, electric vehicle applications have found this to be a promising study topic. The configuration of Double Stator (DS)-PMFSM or partition-stator machine compromised the finer torque density than the single Stator (S)-PMFSM due to double stator's area utilization is increasing. Permanent magnet is often located in an inner stator, while armature coils are typically located in an outer stator [7]. The advantages of this motor's capacity acquire higher torque density and efficiency is significantly superior apart from conventional permanent magnet synchronous machines [8].

In addition to its low cogging torque, this motor possesses a reluctance torque that is insignificant. The cooling of the machine is easier because the rotor is devoid of magnets and winding, with PMs and AC are located on the separate fixed sections [9]. Aside from that, DS machines provide enough capacity for active components to fit in the machine core, as well as multiple options for arranging the components in both stators, so that the machine core may be easily circulated with flux [7, 10]. Even though there are numerous Double Stator PMFSM constructions with a various of stator slot rotor poles configurations that have been explored in the research [11, 12]. H-Rotor is chosen due to its robustness and have low iron and copper losses.

This paper improves the initial design performance of DS-PMFSMs by proposing a H-Configuration modular rotor designed for passenger drone. The focus is on the motor torque performances and modification on the modular rotor design. Torque performance can be analyze by using technique such as notching is applied to the H-Configuration modular rotor design to reduce the cogging torque and achieved sinusoidal back-EMF waveform.

2. H-Configuration DS-PMFSM Design Topology

A design series of step DS-PMFSM with 12 poles in the outer and inner with 20 rotor poles which can make the motor be regarded as inner and outer stator running separately to meet different operational requirement. JMAG- Designer software is utilized to design the proposed segmental rotor DS-PMFSM. Although, 2D FEA solver is implemented for examined the performance of the motors.

2.1 Motor parameter and specification

Figure 1 shows the 12S-20P DS-PMFSM with an ingenious segmental rotor construction. The design requirement and specification are based on modular rotor DS-PMFSM parameter. The parameters of the proposed design are given in **Table 1**.

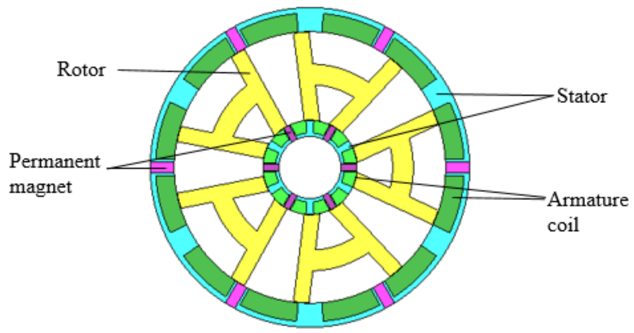

Figure 1: The proposed design of H-configuration modular rotor PMFSM

Table 1: The specification of DS-PMFSM

Description	Value
Inner diameter of inner stator, mm	30.0
Outer diameter of outer stator, mm	154.5
Motor stack length, mm	70.0
PM weight, kg	0.5
Air gap, mm	0.3
Rotor tooth	20
Number of turn of outer Armature coils	107
Number of turn of inner Armature coils	50

2.2 Operating principle of H-configurations modular rotor DS-PMFSM

Initially, the new design machine's operating principle must be performed before continuing to execute the analysis. The coil test should be carried out according to the flux switching concept where U-phase flux is obtained the maximum amplitude is allegedly at 180° degree of electrical cycle from excitation components to obtain the best flux coupling. This test is performed since the suggested machine operating principle has been validated by the results of the coil test. The first step pf performing the coil test is by doing 3 coil test analysis to verify the coil test analysis of each DS-PMFSM armature coil at inner and outer stator. For each of the coil tests, 3 magnetic flux profiles were obtained from armature coil for both stators. Two of the coils from inner and outer stator, must share the same characteristics to accomplish a three-phase armature coil configuration. The orientation of all coils is then configured in such a way that a sinusoidal wave with a 120-degree shift transition phase may be formed. The outcomes of the 3-coil test, each of which has the same flux characteristic, are grouped into three separate flux groups. The armature coil phases are then identified using the three-phase flux connection of U, V, and W independently, by checking at the flux continuity on every coil.

After performing the coil test analysis, the performance analysis of the machine in terms of the back-emf, cogging torque, flux lines and flux distribution are observed in no load analysis. For the load analysis, the motor is observed for its torque performance at various armature current density conditions. The armature current density is varied from 0 to 30 $Arms/mm2$. The calculation of armature current and peak current calculation is shown in **Equation 1** respectively. Then the data calculated will be used by inserting the values into the circuit in JMAG Designer to do the torque performance at various current density conditions.

$$I_A = \frac{\sqrt{2}\, J_A \alpha_A \delta_A}{N_A} \qquad \textbf{Eq. 1}$$

where, Ia is input current of armature coil, α is constant filling factor, δa is area of armature winding slot and Na is number of turns of armature winding. **Table 2** shows the value of armature current and peak current for DS-PMFSM.

Table 2: Peak current value for DS-PMFSM

Armature current density, Ja	Ia, rms	Ia peak
5	10.7255	15.168
10	21.4510	30.3362
15	32.1764	45.5044
20	42.9019	60.6725
25	53.6274	75.8406
30	64.3529	91.0087

2.3 Motor optimization of H-configuration modular rotor DS-PMFSM

Invariably, the motor's initial parameter design does not always accomplish the desired performance. The initial passenger drone design as shown in **Figure 2** produced torque at 45.16 Nm value with non-sinusoidal back-EMF waveform. Thus, positive development and improvement of the rotor design is then assessed and analysed by optimizing the modular rotor with H-configuration design. **Figure 3** illustrates a modular rotor configuration for the DS-PMFSM with 12-Slot stator. The parameter are used as the basis for the design parameters with air gap length remaining constant at 0.3mm. The investigation performance is carried out to discover the outstanding rotor-pole design for achieving maximum torque and sinusoidal induced voltage.

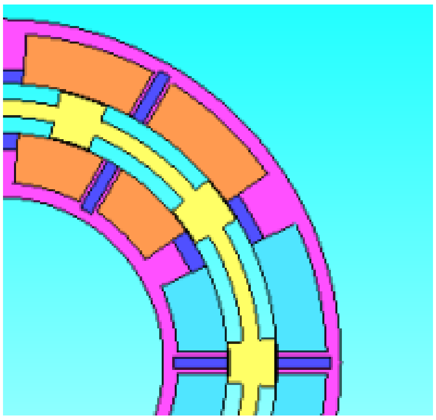

Figure 2: Salient rotor PMFSM

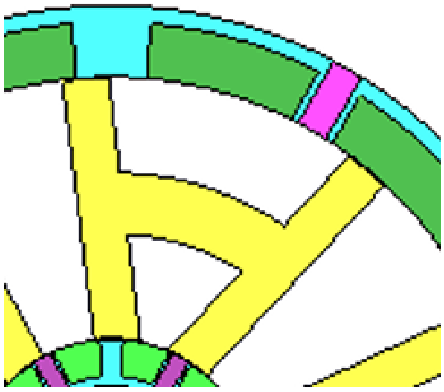

Figure 3: H-configuration modular rotor PMFSM

Apart from modular rotor modification, notching techniques have been applied to help reduce the cogging torque and back emf. The notching technique is one of the local optimization method. It is introduced to the outer surface of the rotor pole. The influence of design characteristics such the rotor pole notching design, number of notches, depth, and width on the cogging torque are investigated. This application may affect the magnitude of cogging torque due to various air gaps between the rotor and stator. Due to its advantages in easy functioning and inexpensive production costs, notching is commonly utilized on the rotor side.

3. Results and Discussion

The result of the proposed design is done with no load and load analysis. Consequently, under no load condition, all the rotor poles configuration is compared in term of U-flux, induced voltage, flux line and distribution, and cogging torque. Then, the average output torque performance is analyzed under load condition.

3.1 Operating principle investigation of modular rotor PMFSM

The operational principle and coil configuration for armature winding in its designated slots is proven by coil testing configuration at no load for the DS-PMFSM modular rotor. 12 armature coils are identified in a balanced three phase (3Ø) system by evaluating a magnetic flux connection on each coil. 6 armature coils winding for inner stator as labelled as C1 until C6 while for outer stator as labelled as C7 until C12 to be set in clockwise direction. From coil test analysis, the two coils from 6 armature coil flux linkage produce the same patterns of DS-PMFSM configuration for double stator. The results for 6 coils are grouped together in a similar set of 2 winding per coil resulting with different three phase of flux linkage called as UVW phase. The armature current density is adjusted to 0 A/mm2, thus only PM generate the overall flux Therefore, the U-Phase waveform is intercepting at the point 90˚ and 270˚ (electrical degree) on x-axis which confirm the no zero-rotor position. Flux switching refers to the process of changing the rotor's flux linkage's polarity after it has completed rotor rotation. The two additional phases, V-Phase and W-Phase are identified by verifying the phase shifted by 120 degrees based upon three phase systems after the determination of U-phase flux.

Figure 4 shows the complete armature coil's polarity and phase, as demonstrated by the 3-flux linkage. The resultant amplitude of the flux created by PM is around 0.07wb which is sufficient for motor function may be viewed from the figure. The waveform of the armature is sinusoidal, confirming the operational principle of DS-PMFSM.

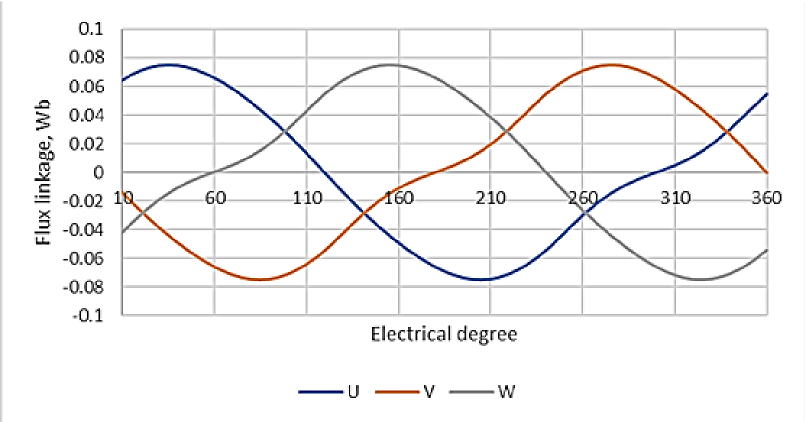

Figure 4: UVW flux linkage

3.2 Torque performanceat various current density conditions

The performance of the machine under load or short circuit condition with a diverse maximum current density of 30A/mm2 for the segmental rotor DS-PMFSM. The results of this evaluation include torque versus armature current density. The inclusion of the H-configuration in the modular rotor 12S-20P DS-PMFSM increase the output torque significantly. The average torque increased to 46.13 Nm after using H-configuration design as shown in **Figure 5** . The cogging torque obtained from no load analysis is 16.12 Nm.

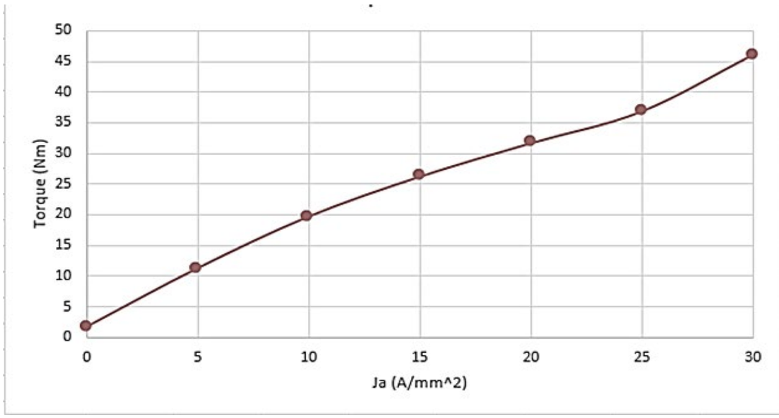

Figure 5: Torque versus current density

4. Conclusion

In this paper, a 12-slot, 20-pole DS-PMFSM rotor employing H-configuration modular rotor relevant results have been analyzed and discussed in detail at no-load and load analysis conditions. As an alternative to the other shapes of modular rotors, a H-configurations modular rotor was selected for the 12S-20P DS-PMFSM because of its low cogging torque, lower ripple torque, and higher torque. However, the torque value of the H-configuration was slightly increase to 46.13Nm. Besides, with this value of torque, this motor is very convenient and suitable to be applied on the passenger drone. For obtain optimal performance of the 12S-20P DS-PMFSM, further research into the modular rotor shape is considered necessary through design refinement and optimization process.

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