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Performance Investigations on Permanent Magnet Synchronous Reluctance Motor for Drone Application

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ABSTRACT

The Synchronous Reluctance Motor (SyRM) has a standout quality such as high Torque density, Wide speed range and simple rotor construction compared to other motors but, this motor suffer with potential torque ripple under certain operating conditions and lower power density compared to PMSM. In this research the comparative investigation among SyRM with and without magnet are implemented to obtain the parameters as Torque, Cogging Torque and Instantaneous Field Distribution. In the configuration with magnets, they were placed in all three layers of the barriers, any two layers of barriers and in only one layer of the barrier. All these machines are modelled and analysed with a common specification as rated current of 36A and rated speed of 6000 rpm. From the above comparison, it is evident that the SyRM with three magnets is superior among other motors and suits for drone application.

Keywords: SyRM, Permanent magnets, Finite element analysis, Torque comparison

INTRODUCTION

The synchronous reluctance motor drive offers an unrestricted speed range, limited only by mechanical factors. To optimize this feature and minimize power losses, a crucial control algorithm is needed. This study introduces a novel voltage control loop, combined with field-oriented current control, ensuring efficient operation within current and voltage constraints across diverse conditions. The proposed algorithm's stability is validated through small signal analysis, simulations, and experimental tests, highlighting its practicality and effectiveness in maximizing the motor's speed range [1]. In response to international efficiency (i.e.) standards, Line-Start (LS) Synchronous Reluctance Motors (SyRMs) are gaining attention. This study examines the benefits of a combined star-delta winding, showcasing higher winding factor and reduced Magneto-Motive Force (mmf) harmonics compared to traditional configurations. The analysis includes LS SyRM and LS ferrite-assisted SyRM with star and star-delta windings, assessing performance indices. Winding function analysis explores design intricacies, while the impact of zero sequence current on motor performance is examined. Experimental validation involves fabricating prototypes of LS SyRMs with star and star-delta windings, with and without ferrite magnets in the rotor. Results from experimental studies closely align with simulation outcomes, affirming the pursuit of IE standards through the exploration of innovative winding configurations [2]. As global temperatures rise, air-conditioner adoption surges, emphasizing the preference for inverter-driven units. This study responds to the demand for efficient motor drives meeting International Efficiency (IE) standards, introducing a cost-effective Permanent Magnet-assisted Reluctance Motor (PMa-SyRM) drive for air conditioners. The proposed drive, featuring a variable-speed rare-earth-free ferrite Al-Ni-Co hybrid PMa-SyRM and a Hall-sensor-based control strategy, enhances efficiency while minimizing costs. Simulation studies and experimental validation affirm the effectiveness and cost-effectiveness of the proposed control compared to conventional methods, addressing the current need for efficient and sustainable air-conditioning solutions [3]. This paper concentrates on discrete-time models and tailored current control strategies for synchronous motors with a magnetically salient rotor structure, encompassing interior permanent-magnet synchronous motors and synchronous reluctance motors (SyRMs). Addressing dynamic performance limitations in low sampling frequency to fundamental frequency ratios, the study introduces an exact closed-form hold-equivalent discrete motor model. An analytical discrete-time pole-placement design method for two-degrees-of-freedom proportional-integral current control is presented, requiring only closed-loop bandwidth and three motor parameters (Rs, Ld, Lq). The robustness of the proposed control design is thoroughly examined and experimentally validated using a 6.7 kW SyRM drive [4].

This article presents a novel control strategy for Synchronous Reluctance Machines (SyRMs), focusing on mitigating parameter saturation related to current. Unlike permanent magnet machines, SyRMs lack rotor magnets, providing cost advantages and increased reliability. The proposed strategy optimizes reference current, considering saturation variations, demonstrated on a 30-slot 4-pole SyRM machine through simulations and experiments [5]. This paper addresses grid code requirements for Wind Energy Conversion Systems (WECS) by proposing a specialized control strategy for achieving Low Voltage Ride Through (LVRT) in a variable-speed grid-connected system using a Synchronous Reluctance Machine (SyRM) as the generator. The study evaluates the efficacy of three control techniques modulation index control, de-loading, and crowbar protection through simulations in the Simulink/MATLAB environment during a three-phase grid fault condition. The proposed strategy integrates field-oriented control for the SyRM, grid voltage-oriented control for the grid-side converter, and a Hill climbing algorithm for maximum power point tracking [6]. This paper introduces an innovative strategy to actively minimize torque ripple in synchronous reluctance machines by utilizing current injection.

Addressing challenges arising from the non-linear magnetic path and rotor core saturation, the proposed technique optimizes injection for active cancellation, demonstrated through comprehensive simulation and experimental evaluations [7]. This paper seeks to identify design parameters for a PM Assisted Synchronous Reluctance Motor (PMASyRM) using cost-effective magnets like hard ferrites, in contrast to those in a reference Permanent Magnet Synchronous Motor stator. The focus is on achieving comparable performance with reduced production costs and applicability for model reference control techniques [8].

ELECTROMAGNETIC ANALYSIS

Without permanent magnets on barriers:

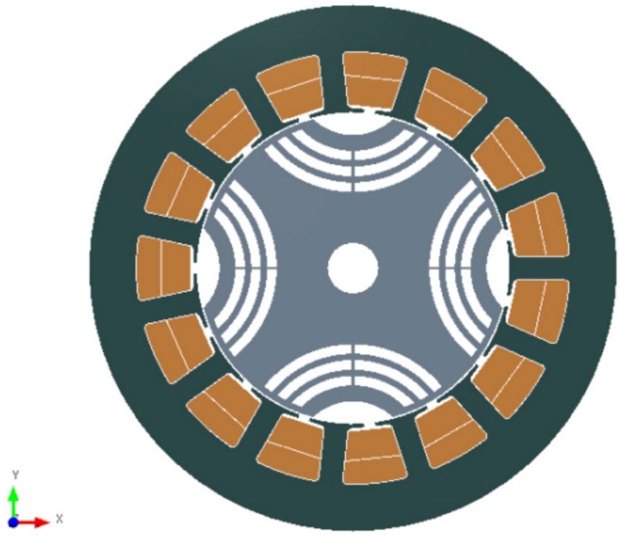


Figure 1 SyRM with Round Barrier Rotor (3 layers)

Figure 1 shows the Synchronous Reluctance Motor with no permanent magnets on round barrier-3 layers, table 1 shows that specifications of SynRM, figure 2 shows that Instantaneous field distribution of SyRM without magnets having a maximum flux density of 2.55 Tesla. Figure 3 shows that the Torque characteristics of SyRM between the torque (N^{-m}) and rotation angle (deg) having a maximum torque value of 1.44 N^{-m}, Minimum torque of 0.16 N^{-m} and average torque of 0.8 N^{-m}.

Table 1 Specification Table

Supply Voltage	24 V
Rated Current	36A
Rated Speed	6000 rpm
Shaft diameter	6.22 mm
Stator type	Square
Stator Outer diameter	65 mm
Rotor type	SynRM with notch and round barrier (3 layers)
Rotor inner diameter	6.22 mm
Rotor outer diameter	38.1 mm
Notch radius	4.08 mm
Stack height	52.4 mm
Air gap thickness	0.35 mm
Number of Stator slots	15
Number of Rotor poles	4
Rotor Magnet angle	25˚

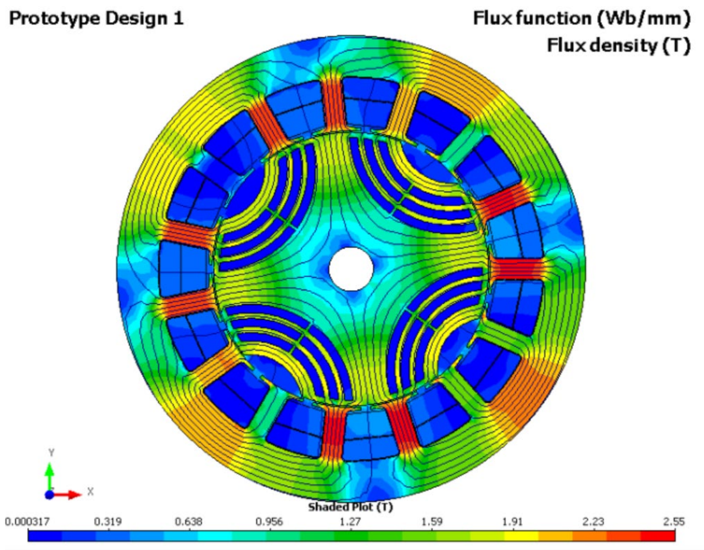


Figure 2 Instantaneous Field

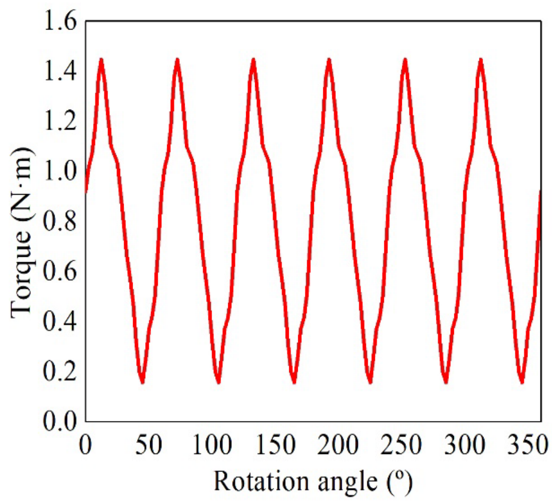


Figure 3 Torque Characteristics

Permanent magnet is placed only one in anyone of the barriers.

Permanent magnet in barrier- Layer 1

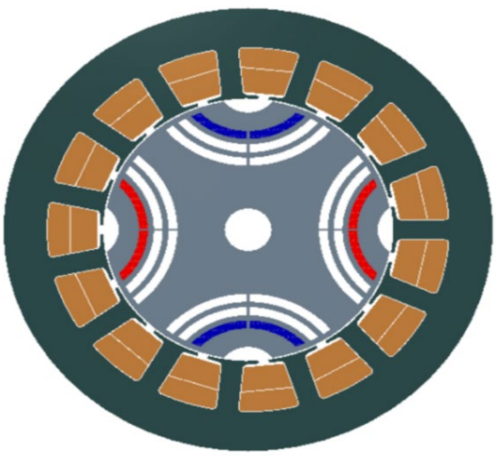


Figure 4 SyRM with Permanent Magnet on Layer 1

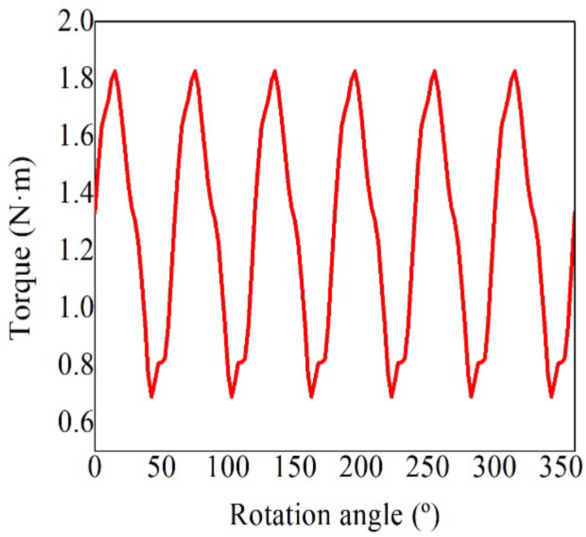


Figure 5 Torque Characteristics

Figure 4 shows that the Synchronous Reluctance Motor with permanent magnets on round barrier- Layer 1. Figure 5 shows that torque characteristics of SyRM with magnets between torque (N^{-m}) and rotation angle(deg) having a maximum torque of 1.83N^{-m}, minimum torque of 0.693 N^{-m} and torque average of 1.26 N^{-m} with 5 deg advance angle.

Permanent magnet in barrier- Layer 2

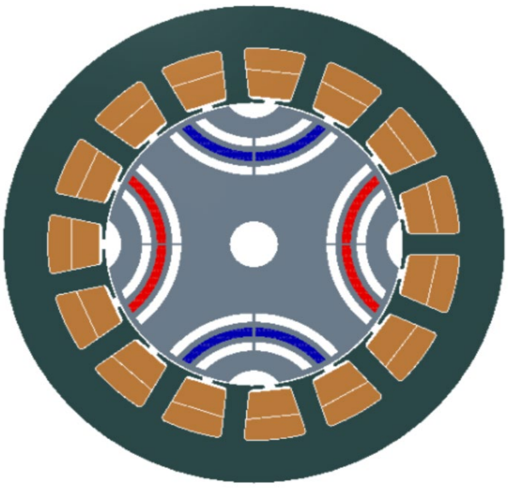


Figure 6 SyRM with Permanent Magnet on Layer 2

Figure 6 shows that the Synchronous Reluctance Motor with permanent magnets on round barrier- Layer 2. Figure 7 shows that torque characteristics of SyRM with magnets between torque (N^{-m}) and rotation angle (deg) having a maximum torque of 1.86 N^{-m}, minimum torque of 0.745 N^{-m} and torque average of 1.3 N^{-m} with 5° advance angle.

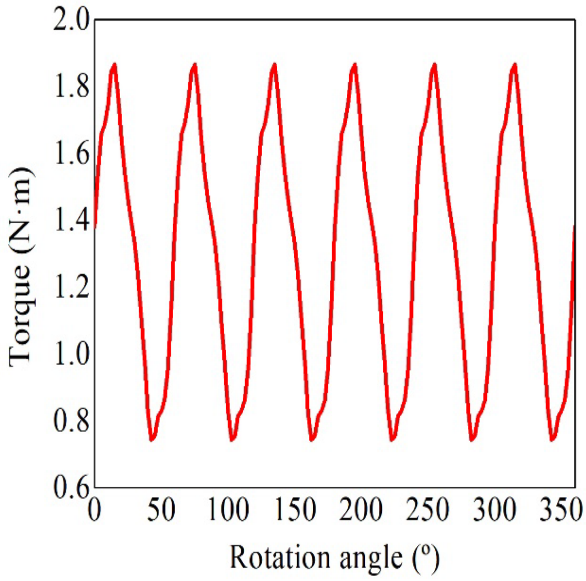


Figure 7 Torque Characteristics

Permanent magnet in barrier- Layer 3

Figure 8 shows that the Synchronous Reluctance Motor with permanent magnets on round barrier- Layer 3. Figure 9 shows that torque characteristics of SyRM with magnets between torque (N^{-m}) and rotation angle (deg) having a maximum torque of 1.88 N^{-m}, minimum torque of 0.773 N-m and torque average of 1.32 N^{-m} with 5 deg advance angle. Figure 10 shows that Cogging torque characteristics of SyRM with permanent magnet in only anyone of the barrier layer having a peak value of 0.25 mN^{-m}.

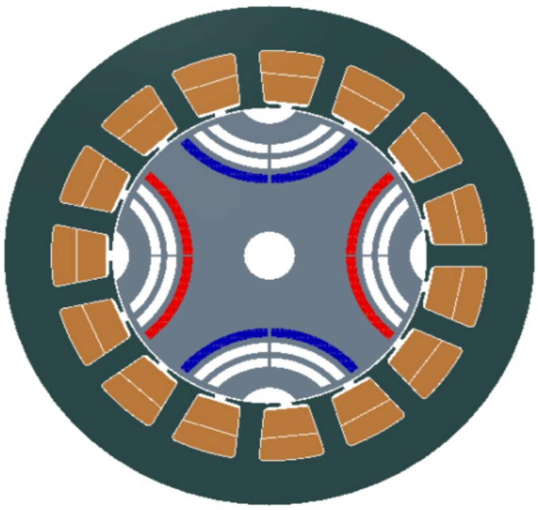


Figure 8 SyRM with Permanent magnet on Layer 3

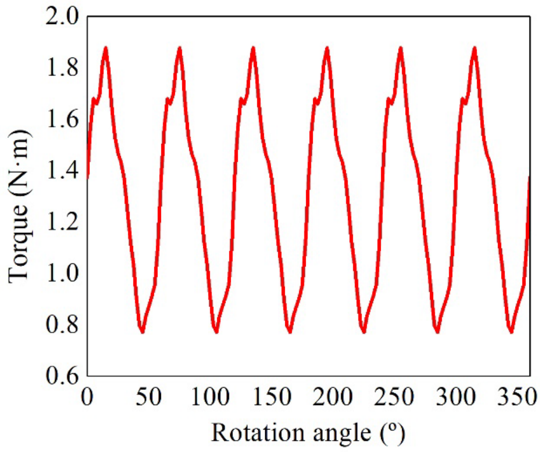


Figure 9 Torque Characteristics

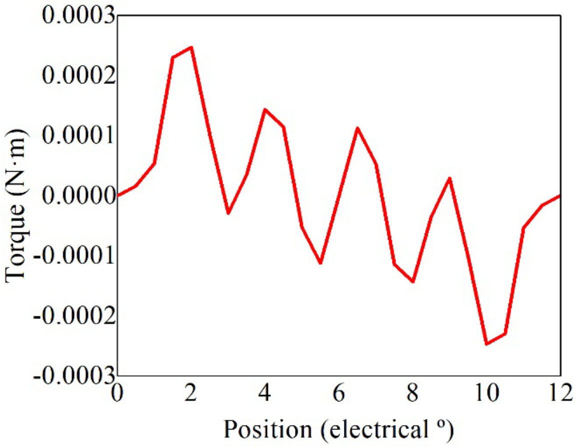


Figure 10 Cogging Torque Characteristics

Permanent magnet is placed in any two of the barriers

Permanent magnet in barrier- Layer 1 and Layer 2

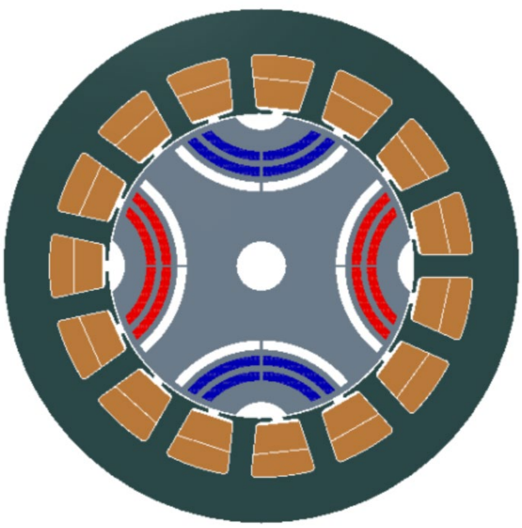


Figure 11 SyRM with Permanent magnet on Layer 1 and Layer 2

Figure 11 shows that the Synchronous Reluctance Motor with permanent magnets on round barrier- Layer 1 and Layer 2. Figure 12 shows that torque characteristics of SyRM with magnets between torque (N^{-m}) and rotation angle (°) having a maximum torque of 1.55 N^{-m}, minimum torque of 0.46 N^{-m} and torque average of 1.0 N^{-m} with 0° advance angle.

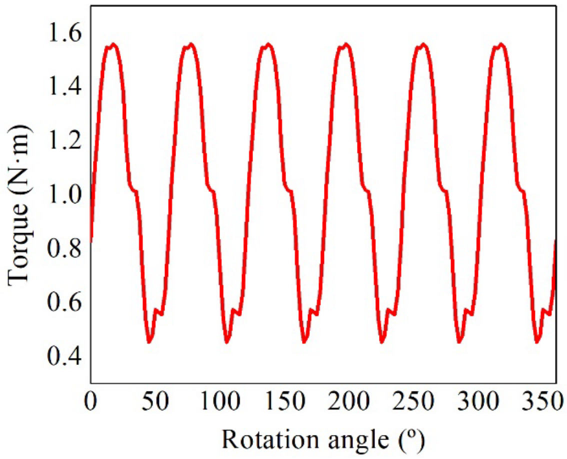


Figure 12 Torque Characteristics

Permanent magnet in barrier- Layer 2 and Layer 3

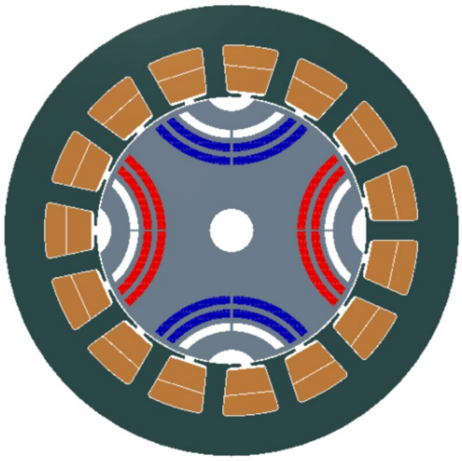
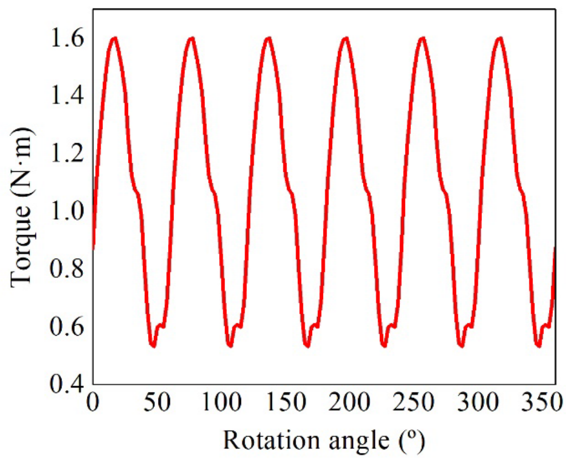


Figure 13 SyRM with Permanent magnet on Layer 2 and Layer 3

Figure 13 shows that the Synchronous Reluctance Motor with permanent magnets on round barrier- Layer 2 and Layer 3. Figure 14 shows that torque characteristics of SyRM with magnets between torque (N^{-m}) and rotation angle (deg) having a maximum torque of 1.6 N^{-m}, minimum torque of 0.53 N^{-m} and torque average of 1.06 N^{-m} with 0° advance angle.



Figre 14 Torque Characteristics

Permanent magnet in barrier- Layer 1 and Layer 3

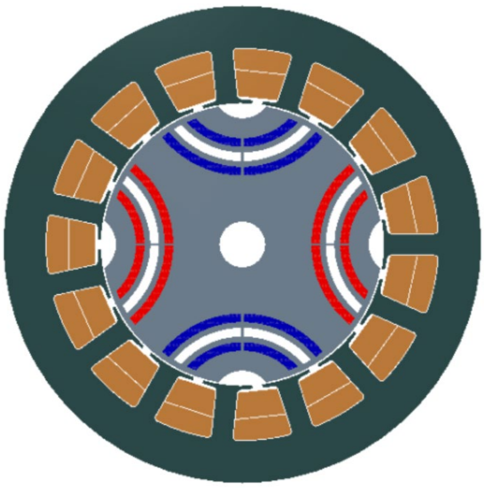


Figure 15 SyRM with Permanent magnet on Layer 1 and Layer 3

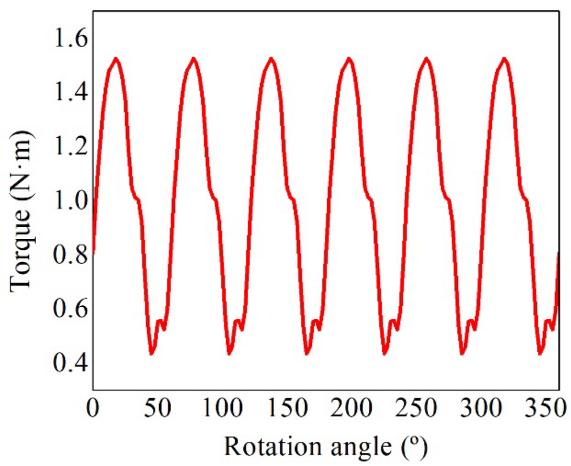


Figure 16 Torque Characteristics

Figure 15 shows that the Synchronous Reluctance Motor with permanent magnets on round barrier- Layer 1 and Layer 3. Figure 16 shows that torque characteristics of SyRM with magnets between torque(N^{-m}) and rotation angle(deg) having a maximum torque of 1.52 N-m, minimum torque of 0.44 N-m and torque average of 0.98 N-m with 0° advance angle. Figure 17 shows that Cogging torque characteristics of SyRM with permanent magnets in any two of the barrier layers between torque (N-m) and position (electrical deg) having a peak value of 0.45 mN-m.

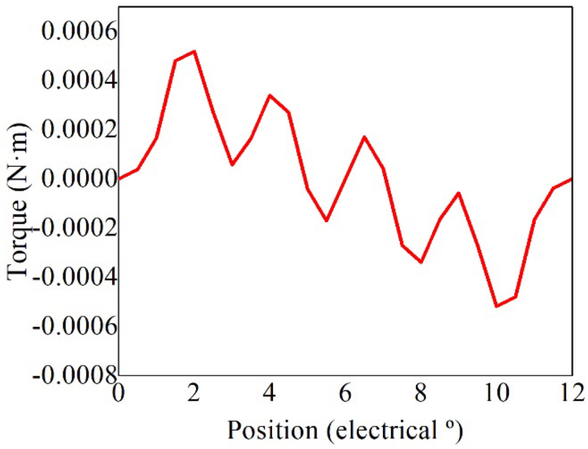


Figure 17 Cogging torque Characteristics

Permanent magnet is placed in all three barriers- Layer 1, Layer 2 and Layer 3

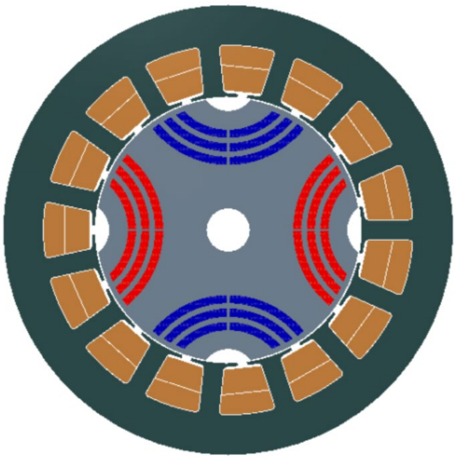


Figure 18 SyRM with Permanent Magnet on Layer 1, 2 and 3

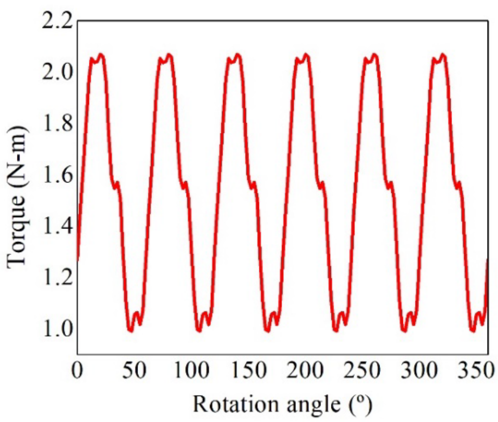


Figure 19 Torque Characteristics

Table 2 Torque Comparison Table

Torque N^{-m}	SyRM without magnet	SyRM with only one magnet in Layer			SyRM with two magnets in Layer			SyRM with Magnet
		1	2	3	1 and 2	2 and 3	1 and 3	
Torque max	1.44	1.8	1.8	1.88	1.55	1.6	1.52	2.07
Torque min	0.16	0.69	0.7	0.77	0.46	0.53	0.44	0.99
Torque avg.	0.8	1.26	1.3	1.32	1	1.06	0.98	1.53

Figure 18 shows that the Synchronous Reluctance Motor with permanent magnets on round barrier- Layer 1, Layer 2 and Layer 3. Figure 19 shows that torque characteristics of SyRM with magnets between torque (N^{-m}) and rotation angle (deg) having a maximum torque of 2.07 N^{-m}, minimum torque of 0.992 N^{-m} and torque average of 1.53 N^{-m} with 0° advance angle. Figure 20 shows that Instantaneous field distribution of SyRM with magnets having a maximum flux density of 2.53 Tesla.

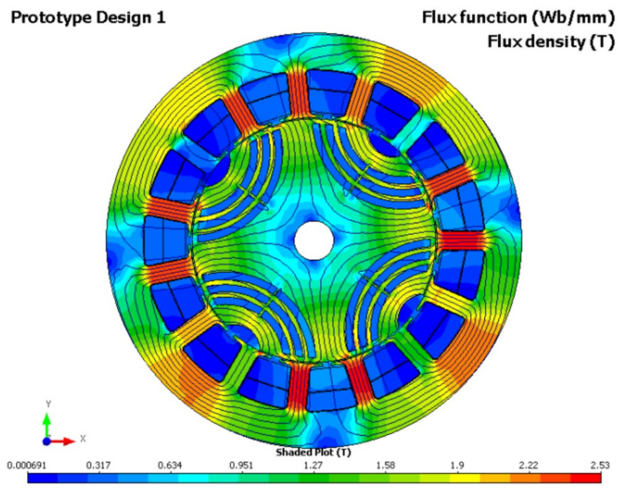


Figure 20 Instantaneous Field

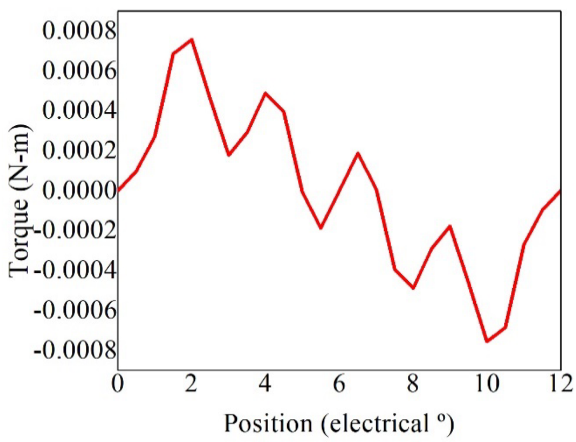


Figure 21 Cogging Torque Characteristics

Figure 21 shows that Cogging torque characteristics of SyRM with permanent magnets in any two of the barrier layers between torque (N^{-m}) and position (electrical deg) having a peak value of 0.78 mN^{-m}. Table 2 torque comparison table of SyRM with and without permanent magnets.

CONCLUSION

Synchronous Reluctance Motors (SyRM) were designed and modeled both with and without permanent magnets. In the configurations with magnets, they were placed in all three layers of the barrier, any two layers of barriers, and in only one layer of the barrier. A comparative analysis of the torque for these motor configurations was conducted to identify the most suitable motor for drone applications. Overall, the SyRM with three permanent magnets exhibited the best torque characteristics and is considered more suitable for drone applications. The average torque of the SyRM with three permanent magnets was found to be 73% higher than that of the SyRM without magnets, 21% higher than the SyRM with one magnet, and 47% higher than the SyRM with two magnets. Additionally, the study investigated the cogging torque characteristics and instantaneous field distribution of SyRM's with magnets and without magnets.

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