INVESTIGATION OF THE INFLUENCE OF FLUX BARRIERS ON THE ELECTROMAGNETIC FORCE AND TORQUE IN A SYNCHRONOUS RELUCTANCE MOTOR

KHẢO SÁT ẢNH HƯỞNG CỦA KHE CHẶN TỪ THÔNG ĐẾN LỰC ĐIỆN TỪ VÀ MÔMEN ĐỘNG CƠ TỪ TRỞ ĐỒNG BỘ

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Tóm tắt:

The Synchronous Reluctance Motor (SynRM) is a type of electric motor that operates on the principle of reluctance. The rotor of SynRM has no windings or permanent magnets. SynRMs are used in various applications: industrial drives, pumps and fans, compressors, HVAC systems. However, the disadvantage of SynRM is high vibration and noise. The electromagnetic force is the main component causing motor vibration. The electromagnetic parameters are calculated to minimize the radial electromagnetic force, which will reduce the vibration and noise, vibration, and harshness of the motor. The number and parameter of flux-barier determines the harmonic amplitude of electromagnetic force. This article aims analyzes the force density and harnomic electromagnetic force of the SynRM motor with 36 stator slot and 4 rotor poles. The electromagnetic forces are calculated by finite element method. Investigation of the influence of different flux barrier dimensions on the radial force and torque ripple of the SynRM. The results show that the dimensions of the magnetic flux barriers are parameters that have a direct impact on the electromagnetic force and torque of the SynRM. Optimizing the flux barrier dimensions can significantly reduce the torque ripple of the SynRM.

Từ khóa:

Electromagnetic force; Flux barier; Radial force; Synchronous reluctance motor; Torque ripple.

Keywords:

Động cơ từ trở đồng bộ (SynRM) là loại động cơ điện hoạt động theo nguyên lý từ trở. SynRM được sử dụng trong nhiều ứng dụng khác nhau: truyền động công nghiệp, máy bơm và quạt, máy nén, hệ thống HVAC. Tuy nhiên loại động cơ này có nhược điểm là độ rung ồn lớn. Lực điện từ là thành phần chính gây ra rung động cho động cơ. Các thông số điện từ được tính toán nhằm giảm thiểu lực điện từ hướng tâm sẽ làm giảm độ rung và tiếng ồn. Số lượng và kích thước của khe chặn từ thông quyết định biên độ của lực điện từ. Bài viết này nhằm mục đích phân tích mật độ lực và biên độ lực điện từ của động cơ SynRM với 36 rãnh stato và 4 cực rôto. Lực điện từ được phân tích bằng phương pháp phần tử hữu hạn; khảo sát sự ảnh hưởng các kích thước khác nhau của khe chặn từ thông đến lực hướng tâm và độ nhấp nhô mô men của SynRM. Kết quả cho thấy kích thước của khe chặn từ thông là thông số có ảnh hưởng trực tiếp đến lực điện từ và mô men của động cơ SynRM. Khi tối ưu được kích thước khe chặn từ thông thì sẽ cải thiện đáng kể về độ nhấp nhô mô men của động cơ SynRM.

Từ khóa:

Lực điện từ; khe chặn từ thông; lực hướng tâm; động cơ từ trở đồng bộ; nhấp nhô mô men.

1. INTRODUCTION

Synchronous Reluctance Motor (SynRM) has high torque density, high efficiency, and dynamic performance for electric vehicle driving systems. Synchronous Reluctance Motors (SynRMs) are finding a wide range of applications due to their efficiency, reliability, and cost-effectiveness. Some of the key applications include: Pumps and Fans, Electric Vehicles, Wind Turbines, Automation and Robotics. SynRM has a clear potential for SynRM to take over significant portion of electrical machine market in the near future to meet efficiency standards in industrial applications without the use of rare-earth permanent magnet technology [1].

The calculation of radial electromagnetic force using the finite element method (FEM) plays a crucial role in understanding the noise and vibration as in [2]. Finding the optimal geometry of flux barrier on rotor for SynRMs in Electric Vehicles (EVs) involves a complex optimization process [3]. Asymmetrical rotor topologies will reduce the order of the lowest spatial harmonic for the radial electromagnetic force and consequently increase the vibration in SynRM [4]. The rotor slot harmonic due to the magnetic potential drop in the flux barriers will produce extra radial force which may cause serious vibration [5].

The different flux path due to the barrier shape, the geometry of flux-barriers is different, leading to reduce the amplitude torque harmonics. [6]. The improving of the electromagnetic torque and efficiency motor by changing the design of the permanent magnet assistance synchronous reluctance rotors [7]. The number of flux barriers can influence the NVH behavior of the motor, a lower number of flux barriers increased the acoustic radiation of the motor [8]. The reduce the torque ripple of SynRM by the improved rotor structure with cross-shaped flux-barriers [9]. In [10], a new rotor structure with multilayer flux barrier to improve performances of torque and levitation force.

However, the contributions of a significant number of harmonics were not considered due to spatial distribution by the different flux barrier.

In this paper, the force density and harnomic electromagnetic force of the SynRM motor with 36 stator slot and 4 rotor poles are analyzed. In addition, the evaluation of geometry flux-barier to weaken the electromagnetic force harmonic orders and improve the acoustic, vibration and torque ripple motor performance.

2. GEOMETRY PARAMETERS OF SYNRM

Determining the diameter of the rotor and the length of the steel core in a SynRM is based on several factors, including the torque requirements for the specific application, efficiency coefficients, and other technical constraints. The electromagnetic torque the evaluation of geometry flux-barier to weaken the electromagnetic force harmonic orders and improve the acoustic, vibration and torque ripple motor performance inertial as [11].

$$T = \frac{\pi}{2} D^2 L_{stk} \lambda \qquad (1)$$

Where: D is the outer diameter rotor, L_{stk} is the stack length and $\lambda = \frac{L_{stk}}{D}$ and λ from 0.8 to 1.25.

The initial parameters of the SynRM 3kW are calculated in Table 1.

Table 1. Geometry parameters of SynRM 3kW

Parameters	Value	Unit
Slot Number stator	36	
Stator outer diameter	152	mm
Stator inner diameter	90	mm
Tooth Width	3.9	mm
Slot Depth	18	mm
Slot conner radius	2	mm
Tooth Tip depth	0.5	mm
Slot opening	2.4	mm
Tooth Tip Angle	300	-
Rotor Pole Number	4	-
Flux barrier Layers	4	mm
Diameter Layer 1, 2,3,4	40,50,60,70	mm
Bridge Thickness layer 1, 2,3,4	1	mm
Out Thickness layer 1, 2,3,4	2	mm
Inner Thickness layer 1, 2,3,4	2	mm
Shaft diameter	34	mm
Airgap	0.3	mm

The flux-barrier effect in electric motors refers to alterations in the magnetic circuit and flux distribution caused by rotor structures. These flux-barriers are essential for distributing the magnetic flux of the rotor, thereby reducing the radial electromagnetic force on the rotor and torque ripple.

This table presents geometry parameters to improve the efficiency and torque which can be best implemented via the FEM method. These parameters are required to ensure a proper data transfer to FEM model.

3. THE RADIAL ELECTROMAGNETIC FORCE

The radial electromagnetic force density in SynRM refers to the force per unit volume acting radially within the motor. This force is a result of the interaction between the magnetic fields generated by the permanent magnets and the currents flowing in the motor windings. It's governed by Maxwell's equations, the Lorentz force law, and the principles of electromagnetism.

$$F_r(\theta, t) \approx \frac{B_r^2(\theta, t)}{2\mu_0} \qquad (2)$$

Where θ is the angular position in the stator steady frame, t is the time, μ_0 is air gap magnetic permeability ; B_r is the radial air gap flux density and it is a function of the rotor angle position, which can be expressed as :

$$B_r(\theta, t) = [f_m(\theta, t) + f_a(\theta, t)]\lambda(\theta, t) \qquad (3)$$

Where, $f_m(\theta,t)$ is the magnetomotive force (MMF) of the permanent magnet, $f_a(\theta,t)$ is the armature MMF, and $\lambda(\theta,t)$ is the air gap permeance.

The magnetomotive force of the permanent magnet is as (4) (ignoring the slotting effect of the stator).

$$f_m(\theta,t) = \sum_{\substack{n=2k+1\\ k=0,1,2,\dots}}^{\infty} F_n \, cos(nk\theta - nk\omega t) \tag{4}$$

Where, p is the pole pairs, w is the angular velocity, and F_n is the amplitude of the nth magnetomotive force.

And the magnetomotive force of the armature as (5).

$$f_s(\theta,t) = \sum_{\substack{\mu=6k\pm1\\ p=0,1,2,\dots}}^{\infty} F_\mu \, cos(\mu p\theta \mp p\omega t) \tag{5}$$

The air gap permeance can be determined as (6).

$$\lambda(\theta,t) = \lambda_0 + \sum_{i=1,2,3,\dots}^{\infty} \lambda_i \cos iZ\theta \tag{6}$$

Where, λ_0 is the amplitude of the static component of the air gap permeance, λ_i is the amplitude of the ith component, and Z is the number of slots.

The vibration amplitude of the motor is closely related to the spatial orders and frequencies of the electromagnetic force, as shown in the following equation:

$$F_r = \frac{P_r}{n^4}\frac{1}{1-\left(\frac{f_n}{f_m}\right)^2} \tag{7}$$

Where, n is the spatial order of the radial electromagnetic force, P_r and f_n is the corresponding amplitude and frequency respectively, and fm is the radial modal frequency of the motor.

4. FEM SIMULATION RUSULT

The 2D model motor is established that is U shape of SynRM model with 36 slots and 4 poles with 4 flux-barrier layers (Fig 1).

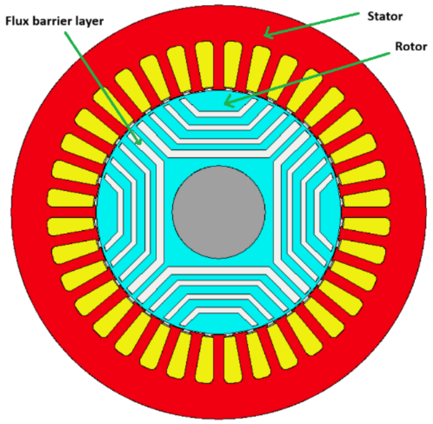

Fig 1. The 2D model SynRM

The result of magnetic flux density distribution of the original motor in fig 2a and the flux density distribution of the improved SynRM in fig 2b.

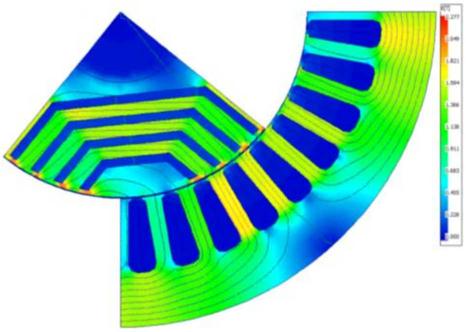

Fig 2a. Path of magnetic flux and flux density SynRM

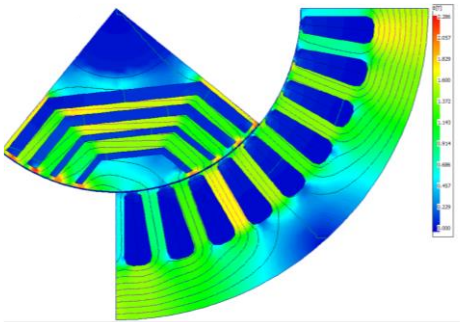

Fig 2b. Path of magnetic flux and flux density improved SynRM

The calculation of radial electromagnetic force using the Maxwell stress tensor equation involves determining the force acting in the radial direction due to the electromagnetic fields within the motor. This force is dependent on the distribution of magnetic flux density, particularly at the middle position of the air gap. Performing a 2-D Fourier transform of the radial force density allows for the transformation of this force from the time-space domain into the frequency-space domain. This transformation provides insights into the force characteristics concerning frequency and spatial orders, enabling easier analysis and visualization of force behavior, as shown in Fig 3 ÷ 8.

An electromagnetic force analysis stator in Fig 3,4,5.

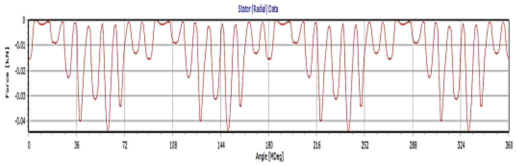

Fig 3. Radial electromagnetic force Stator

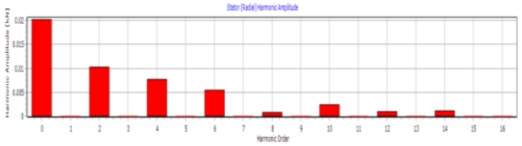

Figure 4. Harmonic components and harmonic amplitude radial force Stator

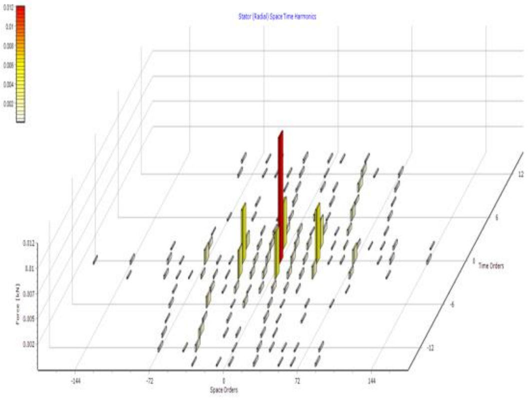

Figure 5. Frequency order and the spatial order result stator

The harmonics of the radial electromagnetic force stator are mainly 2,4,6th and 12th order. These harmonic orders are multiples of the number of rotor poles. The electromagnetic force harmonics arise due to the variation of magnetic flux and the uneven distribution of flux in the air gap. The number of stator slots determines the amplitude of these harmonics. At the same time, the rotor structure, with flux-blocking slots, creates asymmetrical magnetic reactance components, leading to electromagnetic force oscillationsAn electromagnetic force analysis Rotor in Fig 6,7,8.

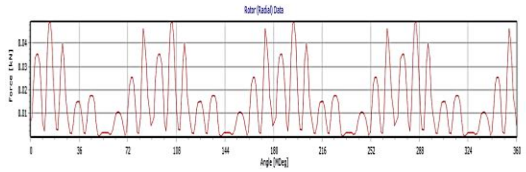

Fig 6. Radial electromagnetic force Rotor

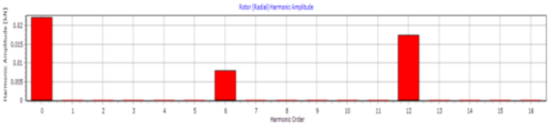

Figure 7. Harmonic components and harmonic amplitude radial force Rotor

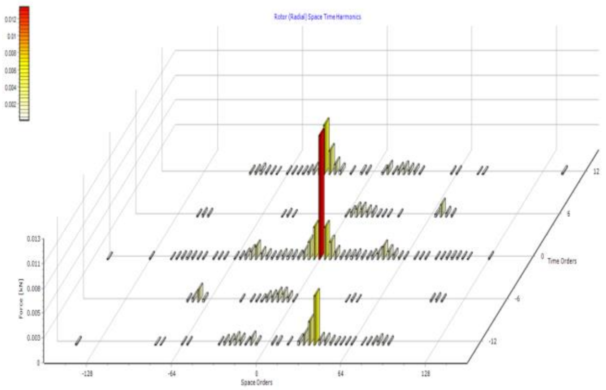

Figure 8. Frequency order and the spatial order result Rotor

The harmonics of the radial electromagnetic force rotor are mainly 6th and 12th order.

In the rotor, the identification of specific spatial orders (such as zero, 6th, and 12th) as the primary contributors to vibration and noise in the motor is valuable information for optimizing the motor's design and operation. Therefore, we only need to pay attention to the harmonics of the zero, 6th and 12th spatial orders, and the higher-order components can be ignored.

It appears that the motor's radial force density analysis focuses primarily on frequency orders that are integer multiples of 2 (even harmonics), while neglecting the constant component (frequency order 0) in the figures. The number of flux barrier layers in the rotor generates the electromagnetic forces that lead to specific force harmonics associated with the identified frequency-spatial order.

The average torque and torque ripple of the initial SynRM are shown in Figure 9.

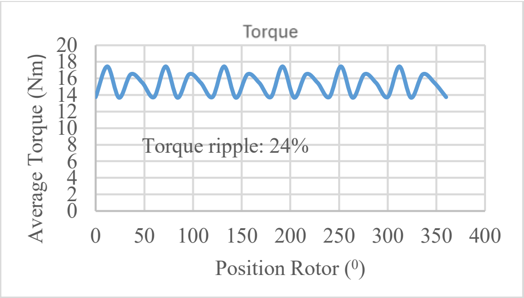

Figure 9. The average torque and torque ripple of the initial SynRM

It can be seen that the amplitude of the radial electromagnetic force with the initial model of the SynRM is still very large, leading to a high torque ripple of 24%. Therefore, it is necessary to minimize the amplitude of the higher-order harmonics of the radial electromagnetic force to reduce the torque ripple to a minimum.

Changing the different geometric dimensions of the flux-barriers will change the magnetic flux distribution and change the radial electromagnetic force, leading to a reduction in torque ripple while still maintaining efficiency and shaft torque.

The parameters of improved SynRM in Table 2.

Table 2. Parameters of Improved SynRM

Parameters	*Intial Value*	*Improved Value*	*Unit*
Bridge Thickness layer 1, 2,3,4	1	1	mm
Out Thickness Layer 1	3	2	mm
Out Thickness Layer 2	2.5	2	mm
Out Thickness Layer 3	1.5	2	mm
Out Thickness Layer 4	1.5	2	mm
Inner Thickness Layer 1	3	2	mm
Inner Thickness Layer 2	2.5	2	mm
Inner Thickness Layer 3,4	1.5	2	mm

The radial force characteristic result of initial SynRM compared to the improvement SynRM is shown in figure 10.

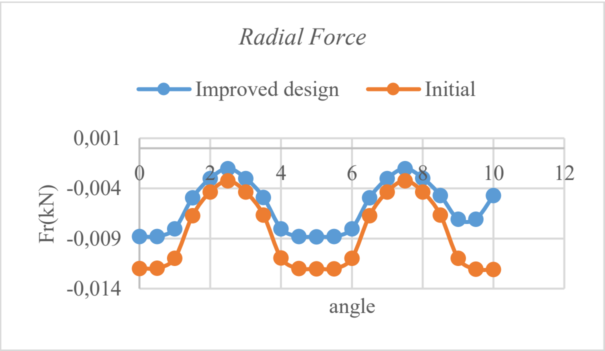

Figure 10. The radial force characteristic of initial and improved SynRM

The results from the figure 5 indicate that after altering the structure of the rotor poles, the electromagnetic force amplitude decreased. Consequently, this reduction led to a decrease in the vibration and noise levels of the motor.

The average torque and torque ripple of the improved SynRM are shown in Figure 11.

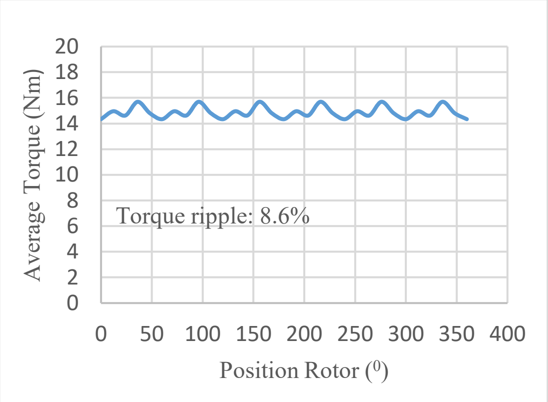

Figure 11. The average torque and torque ripple of the improved SynRM

The above results also show that as decrease in out thickness and inner thickness layer of flux-barrier, the torque ripple significantly decreases: from 24% to 8.6%. The results show that changing the size of the flux barriers reduces the torque ripple by 15%, while the average torque only decreases by 3%.

A comprehensive overview comparing some of the most efficient motor based on torque, and power in the below table 3.

The results in Table 3 shows that when the dimensions of the four flux barriers (arranged sequentially from the rotor center outward) are gradually reduced, the torque ripple is significantly improved—from 24% down to 8.6%.

Table 3 . Result of Overview comparing Initial and Improved SynRM

	Initial SynRM	*Improved SynRM*	*Unit*
Maximum torque possible	15.049	14.563	Nm
Average torque	15.366	14.885	Nm
Torque Ripple	3.6864	1.2771	Nm
Torque Ripple [%]	24.065	8.6145	%
Speed limit for constant torque	2920.7	3024.4	rpm
Electromagnetic Power	4812.6	4657.4	W
Input Power	5141.7	4986.5	W
Total Losses	483.88	478.67	W
Output Power	4657.8	4507.8	W
System Efficiency	90.589	90.401	%
Shaft Torque	14.826	14.349	Nm

Meanwhile, the average torque decreases by approximately 0.45 Nm (about 3%), and the efficiency drops by only 0.2%, compared to the original SynRM model with four flux barriers of equal dimensions.

5. CONCLUSION

The paper presents a method specifically designed to mitigate electromagnetic force orders in SynRM, providing significant value to manufacturers and designers aiming to minimize noise harmonics by reducing radial force. This innovative approach leverages the structural elements of rotor and flux- barier to attenuate the amplitudes of these harmonics, thereby achieving a notable reduction in electromagnetic force orders.

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