Radial force calculation of Switched reluctance motor 5,5kW with skewed slot stator and rotor structure

Phân tích lực điện từ của động cơ từ trở 5,5kW với kết cấu chéo rãnh stator và rotor

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Abstract
Normally, switched reluctance motors can be designed with straight or skew slots due to different applications. Stator and rotor configurations have strong influence the performance of switched reluctance motor such as acoustic noise and torque ripple. The purpose of this paper is to compare and evaluate radial force of rotor straight and skew slots configurations for switched reluctance motor.The switched reluctance motor with both slot structure is minimized torque ripple and vibration.
This paper describes a comprihensive design of a three phase SRMs motor 5,5 kW for electrical drive application. An optimal design of SRMs motor have been implemented by analytical and simulation methods to improve those disadvantages.
Keywords: Switched reluctance motor, skew slot, radial force
Tóm tắt: Động cơ từ trở thường được thiết kế với cấu trúc rãnh thẳng. Với kết cấu stator và rotor như vậy có ảnh hưởng lớn đến độ rung ồn và độ nhấp nhô mômen của động cơ. Lực điện từ sinh ra trên bề mặt cực stator là thành phần chủ yếu gây nên độ rung ồn và độ nhấp nhô mônen của động cơ. Mục đích bài báo là so sánh giá trị lực điện từ sinh ra trên bề mặt cực stator với kết cấu rãnh stator, rotor thẳng và lực điện từ với kết cấu rãnh stator, rotor nghiêng.
Bài báo đưa ra mô hình phân tích, mô phỏng với động cơ từ trở ba pha 5,5kW.
Từ khóa: Động cơ từ trở, rãnh nghiêng, lực điện từ

Symbol

Symbol	Unit	Mean
F_r	N	radial force.
θ	rad	Rotor position
ψ	Wb	Flux linkage
L	H	Inductance
i	A	Current
g	mm	air gap length

Abbreviations

SRM   Switched reluctance motor

1. Introduction

Nowadays, SRMs have been applied in various fields from mechanical machine to electricdrives [1]. However, the switched reluctance machines are still two disadvantages of high torque ripple and acoustic noise. Thetorque ripple can be reduced by shaping torque control strategy orskewing slots of the SRMs[2,3]. Moreover, the force harmonics generated by thetorque ripple are much smaller than those caused by the radial force [4,5].

In this paper,an electromagnetic radial force model with straight and skewed slots is built to investigate magnitude of electromagnetic radial force and vibration. In conclusion, an optimal skew angle can be define to minimize noise and torque ripple.

2. Analytical method for radial rorce calculation

Radial force depends on electromagnetic energy change in air gap. The force is highly changed at turn on and off angles. Those forces will press and stress the stator and rotor poles to deform the SRM structure. Therefore, radial force F_r can be expressed as:

$$F_r = \frac{dW_m}{dl_g} \qquad (1\text{-}1)$$

$$W_m = \frac{1}{2} i^2 L(\theta, i) \qquad (1\text{-}2)$$

Where:

W_m- storage magnetic energy in air gap,
l_g - air gap length between stator and rotor;
θ - rotor position;
i - phase current,
L(θ,i) - self inductance of single phase.

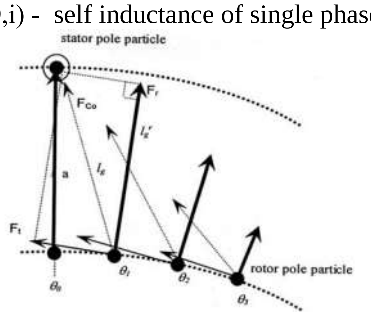


Fig1*: Vector diagram of force between stator and rotor $\theta = \theta_0$, $F_{r0} = F_{max}$, $F_{t0} = 0$*

For simple analysis, relation between $L(\theta,i)$ and l_g can be considered as

$$\frac{dL(\theta,i)}{dl_g} \approx -\frac{L(\theta,i)}{l_g} \qquad (1\text{-}3)$$

Where minus sign indicates decreasing trend of air gap pressed to inductance. After inserting expression of $W_m$into E_q. (1-3), electromagnetic RF can be expressed as

$$F_r(\theta, l_g, i) = -\frac{1}{2} i^2 \frac{L(\theta,i)}{l_g} \qquad (1\text{-}4)$$

In vector variation of RF between stator and rotor (Fig.1.1), stator and rotor poles are consideredparticles. Stator particle is fixed and rotor particle is rotating with motor axial. Vector distance between two particles is defined as air gap length,l_g.Air gap length in radial direction is component l_g^r to calculate RF [6]. In terms of geometry relation, aligned position of stator and rotor poles is defined at zero angle positionθ_0, when rotor particle rotates away from aligned position θ_0. Air gap length l_g^rcan be calculated as

$$l_g^r = (r + a)\cos\theta - r \qquad (1\text{-}5)$$

Where

r, outer radius of rotor;

a, vertical distancebetween two particles at θ_0.

Considering dimension effects of stator pole height and rotor pole height.

$$a = \frac{h_g + h_r}{2} + g \qquad (1\text{-}6)$$

So, air gap length in redial direction is given as

$$l_g^r = \left(r + \frac{h_g + h_r}{2} + g\right)\cos\theta - r \qquad (1\text{-}7)$$

Comparing with outer diameter of stator, l_g^r is small.

Assume a = 0, Eq. (1-7) becomes:

$$l_g^r = r(1 - \cos\theta) \qquad (1\text{-}8)$$

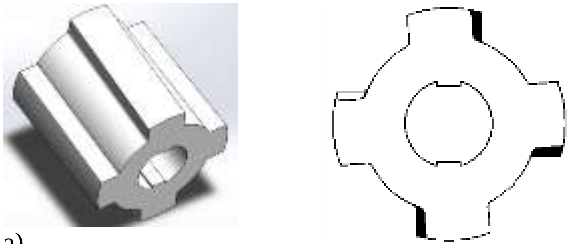
Thus analysis of electromagnetic RF can be given by a nonlinear function of θ and *ias*

$$F_r = -\frac{1}{2} i^2 \frac{L(\theta,i)}{r(1-\cos\theta)} \qquad (1\text{-}9)$$

Once phase current i is fixed to be a constant value, and self-inductance L gets maximum value at aligned position, then RF will rise with increasing rotor position (aligned position is defined as =0°). Rotor position angelis $\theta_0 = 0^0 < \theta_1 < \theta_2 < \theta_3$ and RF is $F_{r0} = F_{rmax} > F_{r1} > F_{r2} > F_{r3}$, where $F_{r0}$is maximum value of RF at aligned position. Due to different rotor positions. RF vector vary along with rotation of motor of axial.

When Skewed slot Structure of Rotor: Rotor structures with skewed slots are shown with 3-D (Fig 2a**)** and 2-D (Fig 2b) views. Enough space between skewed slots to insert windings will not affect whole structure of SRM. Maximal alternate angle of rotor skewed slots is 5°, which cannot be designed too large. It will affect torque output. In terms of simulation, an appropriate selection scope of alternate angle is 4~5°. For easy understanding, assume rotor made up of n pieces laminations, and m is the m^th^ piece alternate lamination. F_{rco} is co-force of all partial radial force (Fig. 3).

$$F_{rco} = F_{r1}\left(\theta - \frac{5}{n}\right) + F_{r2}\left(\theta - \frac{2\times 5}{n}\right) + \cdots + F_{rm}\left(\theta - \frac{m\times 5}{n}\right) \qquad (1\text{-}10)$$



a) b)

Fig 2- Skewed slot structure of rotor with: a) 3-D and b) 2-D view

3. Static calculation of Radial Force

For complexity structure of SRM and highly saturated nature of flux density, it is very difficult to model and calculate normal force analytically and accurately. Thus, nonlinear ANSYS software was used to calculate static structural and electromagnetic problems. Static radial force calcution is shown with initial structure (straight slots for rotor) for 30 angles ($\theta = 30^0$) (Fig 1.3) .It was observed that static radial force decreased effectively.

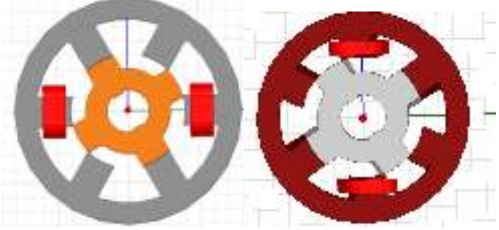
4. Simulation and result

For verifying concept of reducing radial force with skewed slot structure, a 5,5kW four phase 6/4 poles SRM was analyzed for simulation (Table 1).

Table 1- *Main dimensions of SRM*

Quantity	Value
Stator out –diameter (D_s), mm	160
Rotor out –diameter (D_r), mm	80
Axial length (L_{Fe}), mm	200
Air –gap (g) , mm	0,4
Stator polar arc (β_s), rad	0,52
Rotor polar arc (β_r), rad	0,78
Rotor axial diameter (D_i), mm	30
Stator yoke height (h_{cs}), mm	15
Rotor yoke height (h_{cr}), mm	15
Stator slot depth (d_s)	24,6
Wings turns number (N_t)	110
Rated power (P), kW	5,5

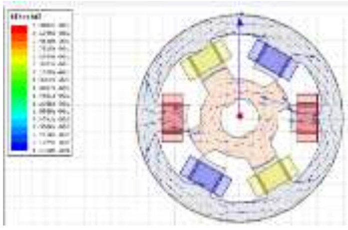
The 3D model was set up by Ansoft Maxwell based on geometry parameters and magnetic characteristics of materials as fig 3.



a) b)

Fig 3. *The 3D model of SRM with straight slot structure (a) and skewed slot structure (b).*

The simulation results of flux density and radial force have obtained after applying transient model. flux density result is shown in fig 4 and radial force is shown in fig 5 repectively.



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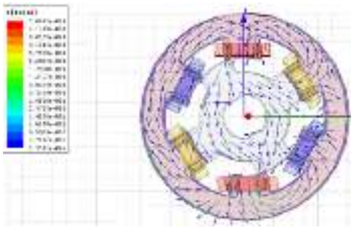

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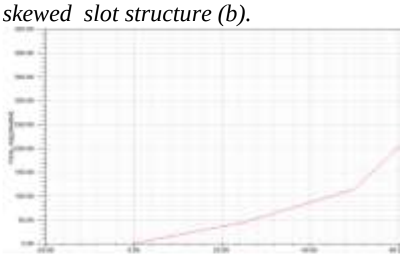
Fig 4: *Flux linkage with straight slot structure (a) and skewed slot structure (b).*



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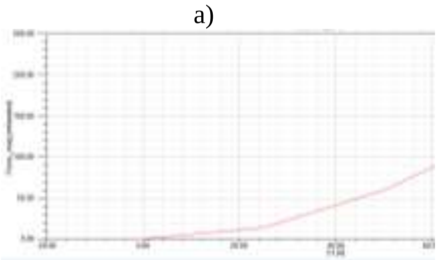

b)

Fig 5. *Radial force waveform with straight slot structure (a) and skewed slot structure (b).*

Simulation results show that the radial force with skewed slot structure smaller radial force with straight slot structure . Therefore switched relactance motor with skewed slot structure will be reduced vibration and acoustic noise.

5. Conclusion

Electromagnetic radial force was investigated and reduce using skewed slot structure designed for rotor of SRMs structural and electromagnetic finite element methods were to model and analyze radial force. Simulated results showed that radial force extensively.

This is optimal design of SRMs motor have been implemented by analytical and simulation methods to improve those disadvantages.

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