INVESTIGATING INFLUENCES OF TAPPED SHOE ROTOR POLES ON ELECTROMAGNETIC TORQUES AND RADIAL FORCES OF SWITCHED RELUCTANCE MOTORS

Bui Minh Dinh*, Nguyen Huy Phuong, Dang Quoc Vuong

Abstract: *The shape of rotor poles has a significant influence on the performance of electromagnetic torques and radial forces, because the air-gap flux density is depent on the stator and rotor areas and surfaces. Serveral articles have studied influences of the stator/rotor designs on radial forces and electromagnetic torque waveforms as well. Moreover, the electromangetic characteristics of switched reluctance motors are also defined by tapped-shoe-skewing of the stator and rotor poles with the inner holes. However, the total solution designs of the tapped-shoe rotor with diferent tapped angles have not yet implemented by those papers so far. For that, in this paper, the tapped shoe rotor pole design is proposed by different angles for the high speed switched reluctance motor of 30 kW and 18000 rpm.*

Keywords: Tapped-Shoe Pole; High Speed Switched Reluctance Motor; Electromagnetic Torque; Radial Force; Finite Element Method.

1. INTRODUCTION

Nowadays, the switched relectuance motors (SRMs) have been widely applied in many fields of industries, i.e., from automotive vehicles to the aircraft engine areas. The SRM is indeed a brushless synchronous machine with the salient rotor and stator poles, concentrated phase windings, and no magnets or rotor windings [1, 6]. The design of rotor poles plays an important role in designing of the SRM. In this paper, a three phase SRM 6/4 (where the stator has 6 poles and 4 poles for the rotor) with the rotor tapped-show is varied for both static and dynamic models to evaluate their effects on the average torque, radial force and efficiency. A new design of the SRM 6/4 has been recently developed by many authors via the conventional motor manufactured [3].

2. CONVENTIONAL AND PROPOSAL DESIGNS

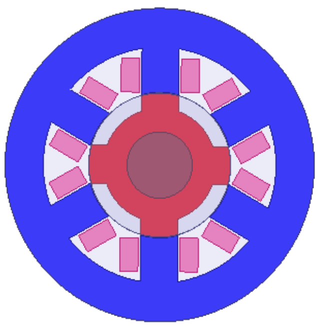

Figure 1. *The normal model of the SRM 6/4.*

The normal model of SRM 6/4 is presented in figure 1 with the geometry parameters shown in table 1. Static torque curves have been investigated by a finite element method (FEM) with the phase current from 200 A to 300 A. The maximum and average torque values with different rotor/stator angles have been simulated by the FEM immersed in 2D ANASYS Maxwell [7]. The influence of rotor/stator pole embrace on the leakage flux and the electromagnetic torque are determined by various pole embrace values to obtain the optimum solution. In this study, the ratio values of rotor and stator embraces per a pole angle are varied from 0.3 to 0.6 with step of 0.05 values as shown in figure 2.

Based on these results, the combination of the rotor pole embrace of 0.4 (0.5x$360^0/N_r$ $=36^0$, where N_r is the pole number of rotor) and the stator pole embrace of 0.5 (0.5x$360^0/N_s$=300, where N_s is the pole number of stator) can be created the maximum static torque values. According to these combinations, the optimum values of stator/rotor pole arcs can be selected for a better motor design. The SRM 6/4 shoe-tapped rotor poles have pole angles of 36^0 degree for the rotor and 30^0 for the stator.

Table 1. *Geometry of the SRM design.*

Name	Symbol	Value	Unit
Number poles of the stator/rotor	N_s/N_r	6/4	-
Stator pole angle	β_s	30^0	-
Rotor pole angle	β_r	36	
Air gap	g	0.5	mm
Outer diameter Rotor	D	80	mm
Outer diameter Stator	D_0	160	mm
Rotor shaft diameter	D_{sh}	30	mm
Yoke thickness stator	b_{ys}	15	mm
Yoke thickness rotor	b_{yr}	15	mm
Length core	L	80	mm
Turns per pole	T_{ph}	11	
Rated speed	n	27000	rpm
Steel type	M250-35A		
Supply voltage	U	250	VDC

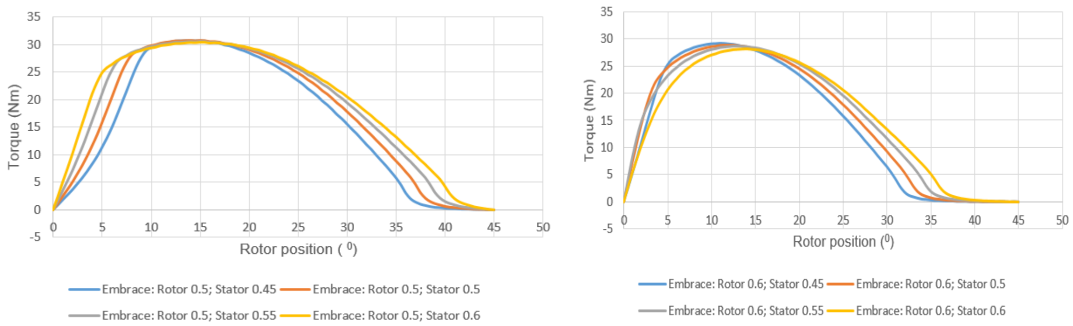

Figure 2. *Output torque of the SRM for different stator pole embraces at 0.5 (left) and 0.6 (right) rotor pole embraces.*

3. SRM SHOE-TAPPED POLE DESIGN

The proposal motor model is shown in figure 3. It is an ordinary 3-phase 6/4 SRM and the material weight of the SRM components have been adjusted to satisfy the requirements shown in table 2.

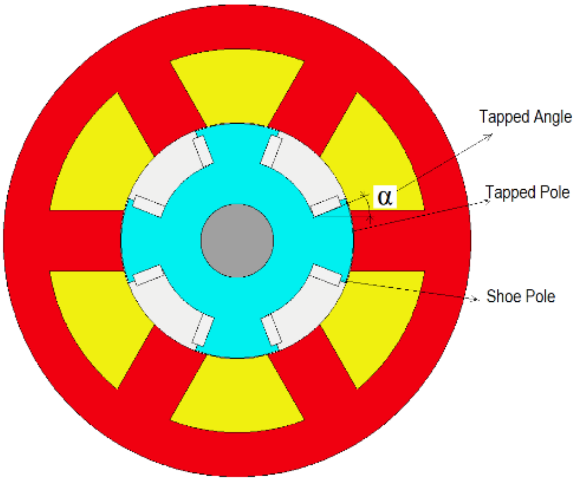

Figure 3. *SRM 6/4 Shoe-Tapped Pole Design [7].*

Main components of the SRM 6/4 consist of the stator/rotor core and three phase windings, where the total weight is 11.73 kg. In order to investigate the dynamic performances, a dynamic model is installed to obtain the torque ripple, flux leakage and efficiency.

Table 2. *SRM material weights.*

Parameters	Material	Weight (kg)
Stator back	M250-35A	4.208
Stator tooth	M250-35A	1.926
Total stator core		6.135
Armature winding	Copper (Pure)	2.04
Front winding	Copper (Pure)	0.7321
Rear winding	Copper (Pure)	0.7321
Total winding		3.504
Rotor back iron	M250-35A	0.9814
Rotor inter back iron		4.47E-06
Rotor tooth	M250-35A	0.6472
Rotor inter tooth		2.95E-06
Total rotor core		1.629
Shaft [Active]		0.3178
Total		11.73

The main blocks of the dynamic model are pointed oun in figure 4 included:

- A firing angle controller
- A CPLD based chopping current controller
- Static torque block
- The non-linear SRM model.

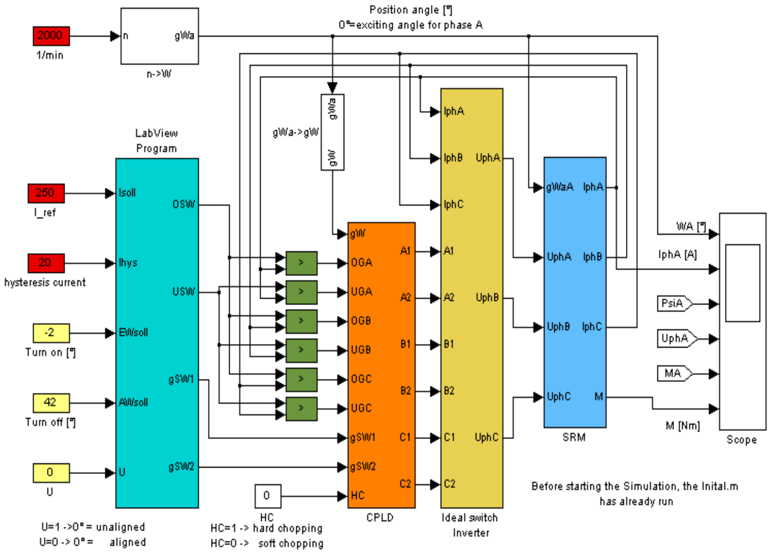

Figure 4. *Modeling of the dynamic case.*

The radial force and rotor curves with different currents (from 20 A to 300 A) are also computed in this model. The electromagnetic radial and tangential forces can be calculated by the flux density variables. The tangential and radial forces in the air gap can be expressed as [2];

$$f_t = \frac{1}{2\mu_0} 2B_r B_t; \ f_r = \frac{1}{2\mu_0}(B_r^2 - B_t^2), \tag{1}$$

where parameters f_t and f_r are the tangential and radial force densities, respectively. The terms B_t and B_r are respectively the tangential and radial magnetic intensities from the tangential direction and vertical direction. The torque acting on the rotor pole can be written as [4, 5]:

$$T_t = F_t \frac{D_{ro}}{2} = \frac{D_{ro}}{2} \int_s f_t ds = \frac{D_{ro}}{2\mu_0} \int_s B_r B_t ds \tag{2}$$

Table 3. *SRM 6/4 electromagnetic performance comparison.*

Parameters	Unit	Normal design	New design
Maximum Torque Possible	Nm	48.466	48.6722
Average torque	Nm	21.642	25.0111
Torque Ripple	Nm	12.223	5.9376
Torque Ripple	%	57.93	23.812
Electromagnetic Power	Watts	916.1	1022.5
Input Power	Watts	301092	32198.8
Output Power	Watts	25220	26922.58
Total Losses (on load)	Watts	5872.7	5276.22
System efficiency	%	81.11411	83.61361
Shaft Torque	Nm	26.945	27.7685
Radial Force max	kN	0.37	0.34
Tangtial Force max	kN	0.165	0.153

The radial force value in the new design is 0.34 kN being less 10% in comparison with the radial force of 0.37 kN in normal or conventional designs shown in table 3. The power and torque results are obtained at the speed of 18000 rpm and normal operation. The dynamic torque curves are simulated by the FEM as shown in figure 5.

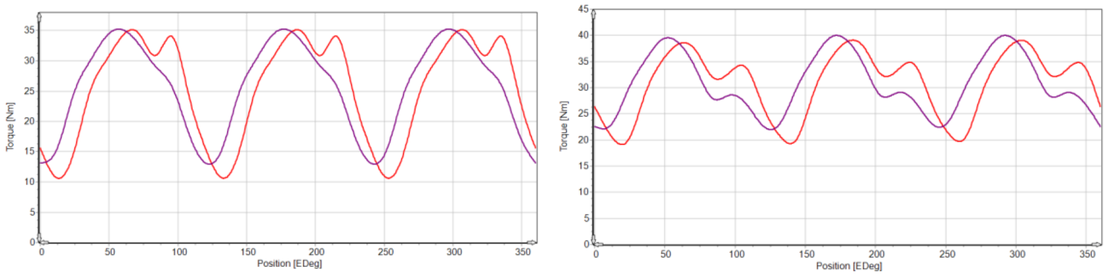

Figure 5. *Torque waveforms with conventional model (left) and new model (right).*

The torque values of the new design is from 40 N.m to 20 N.m (torque ripple of 20 Nm) while the torque values of the normal design are from 35 down to 10 Nm (torque ripple of 25 Nm). The peak power and torque with the current density of 18 A/mm2, the peak torque and power and speed curves are shown in figure 6. The maximum power is 60 kW with the rated power of 30 kW.

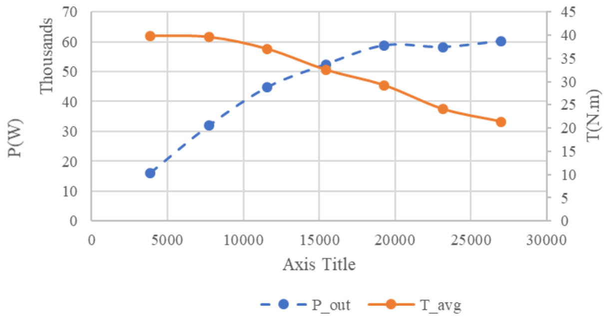

Figure 6*. Characteristics of the peak torque and power.*

The turn on and turn off angles are determined via an equation (3) in linear model [7-9]:

$$\begin{cases} T_{on} = \theta_{on} = -N_r N_s(\beta_r - \beta_s) \\ T_{off} = \theta_{off} = 180 - N_r N_s(\beta_{r-}\beta_s)' \end{cases} \tag{3}$$

In order to obtain the maximum torque per/ampere, the turn on and turn off angles must be adjusted and the turn on and off curves are implemented in figure 7.

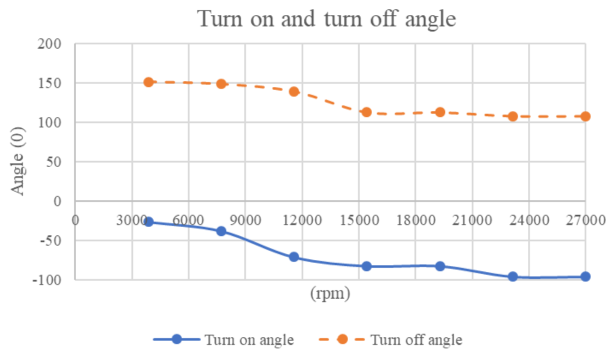

Figure 7*. Turn-on and turn-off angles and speed.*

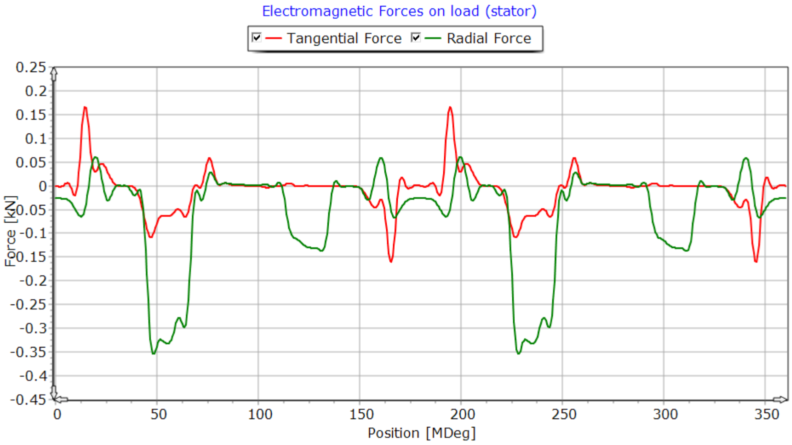

Figure 8. *Tangential and radial forces and the rotor position.*

In order to analyze the radial force waveforms, the both radial and tangential forces calculated under the peak power with current of 300 A as presented in figure 8. In one cycle, the radial and tangential forces are generated or pulsed by two times because those forces created in between rotor in/out stator pole.

4. CONCLUSIONS

The article has analyzed the stator and rotor embraces/pitch influenced on the average torque and torque ripples by the FEM to find out the rotor/stator pole angles.

The torque waveforms have been successfully presented with both conventional model and new model. The turn on and turn off angles are then determined via the linear model. The best combination of the rotor pole and stator pole embraces can be obtained the maximum static torque values. The two models of different normal, tapped-shoe pole topologies for the high speed SRM of 30 kW and 18000 rpm have been simulated to evaluate the torque and efficiency performances. The radial and tangential forces are also compared to check the validation of the proposed method.

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TÓM TẮT

KHẢO SÁT ẢNH HƯỞNG CỦA HÌNH DẠNG CỰC TỪ ROTOR-VÁT GÓC ĐẾN MÔ MEN ĐIỆN TỪ VÀ LỰC HƯỚNG TÂM CỦA ĐỘNG CƠ TỪ TRỞ

Hình dạng các cực từ rotor ảnh hưởng đến đặc tính mômen điện từ và lực hướng tâm của động cơ từ trở vì mật độ từ thông trên khe hở không khí phụ thuộc vào bề mặt và biên dạng cực từ rotor và stator. Một số bài báo đã nghiên cứu ảnh hưởng của thiết kế stator/rotor lên lực hướng tâm và các dạng sóng mô-men điện từ tổng. Hơn nữa, các đặc tính điện từ của động cơ từ trở cũng được xác định bằng cách chéo rãnh cực hay đục lỗ bên trong rotor và stator. Tuy nhiên, toàn bộ giải pháp thiết kế rotor cực lồi-vát góc với các góc khác khác nhau vẫn chưa được các tác giả nghiên cứu. Trong bài báo này, thiết kế cực rotor cực lồi-vát góc được đề xuất theo các góc khác nhau cho động cơ từ trở tốc độ cao (30 kW-18000 vòng/phút).

Từ khóa: Cực từ lồi-vát góc; Động cơ từ trở tốc độc cao; Mô men điện từ; Lực hướng tâm; Phương pháp phần tử hữu hạn.

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