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Modeling of Novel Permanent Magnet Pole Shape SPM Motor for Reducing Torque Pulsation

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This paper deals with the modeling of a novel permanent magnet (PM) pole shape for a surface-mounted permanent magnet (SPM) motor so as to generate sinusoidal back EMF and linear electromagnetic torque. Conventional SPM motors have a square-shaped PM pole structure; therefore, square back EMF is generated along with the torque pulsations. This novel SPM motor has sinusoidal PM pole shape in the axial direction; therefore, sinusoidal back EMF is generated due to the sinusoidal magnetic flux distribution. Sinusoidal back EMF eliminates most of the cogging torque; thus, a linear electromagnetic torque is generated. Square and sinusoidal current excitation is provided as to analyze the electromagnetic torque characteristics of SPM motor models. As compared to square current excitation, sinusoidal current excitation shows better linearity as well as average electromagnetic torque for the novel SPM motor model. 3-D finite element analysis (FEA) is utilized to analyze and compare the back EMF, cogging torque, and electromagnetic torque of conventional and proposed novel PM pole shaped SPM motor models for both square and sinusoidal current excitation.

***Index Terms*—Cogging torque, linear electromagnetic torque, permanent magnet (PM) pole shape, sinusoidal back EMF, surface-mounted permanent magnet (SPM) motor.**

I. Introduction

PERMANENT magnet (PM) brushless machines are increasingly used in domestic and industrial applications, where adjustable speed, high performance and good positioning control characteristics are required [1], [2]. As torque smoothness is an essential requirement in wide range of high performance applications [3]. Therefore, special consideration is required to minimize the torque pulsations so as to generate a linear electromagnetic torque. Torque pulsations include both cogging torque and torque ripples.

In SPM motors, cogging torque is especially of high concern because it is often a principal source of vibration, noise and control difficulty [1]. Cogging torque is produced either due to the non-uniform stator windings or magnetic flux distribution. There are two methods to decrease the cogging torque, either by compensating electromagnetically by adapting the drive current waveform to produce an electromagnetic torque ripple component that cancels the cogging or by modification of the motor design. Thus, the motor design should be modified such that stator windings should be sinusoidally distributed around the air gap and/or the radial magnetic flux density varies sinusoidally along the air gap [3], [4]. Suitable design methods have been adopted to reduce the torque pulsations such as a suitable combination of number of slots and poles, changing the design parameters of armature such as skewing, teeth pairing, different slot openings, and changing the design parameters of PM poles such as suitable selection of pole arc coefficient, magnet shifting, magnet skewing, etc [4], [5]. Suitable combinations of the number of slots and poles for changing the circuit parameters of the armature for a sinusoidal stator winding distribution is either limited to surface-mounted permanent magnet (SPM) motors with larger slot numbers or to configurations having winding complexity [5]. Similarly, changing the design parameters of a PM pole either increases the cost and structure and manufacturing complexity or decreases the power density of PM motors [3]–[5].

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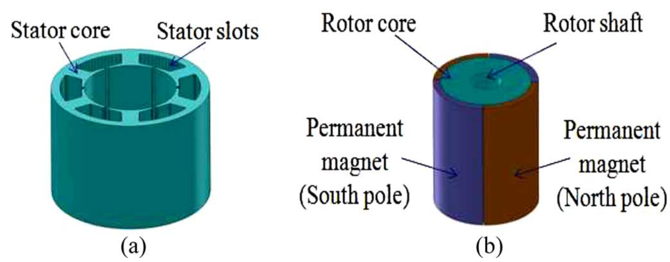

Fig. 1. Conventional SPM motor structure. (a) Stator. (b) Rotor.

In this paper, a novel PM pole shape is presented for producing the sinusoidal magnetic flux distribution in the air gap so as to generate the sinusoidal back EMF and eliminate most of the cogging torque, for linear electromagnetic torque generation. Finally, 3-D finite element analysis (FEA) is utilized to analyze and compare the conventional and proposed novel PM pole shaped SPM motor models at both square and sinusoidal stator current excitation source.

II. SPM Motor Modeling

A. Conventional SPM Motor Model

A conventional SPM motor has a simple three phase concentrated coil winding distribution and square shaped permanent magnet poles, wherein the structures of stator and rotor are shown in Fig. 1(a) and (b), respectively. The stator is slotted with six slots for concentrated coil windings and four rectangular shaped permanent magnets are mounted at the surface of rotor core. In addition, design parameters of a conventional SPM motor are shown in Table I.

B. Proposed SPM Motor Model

1) Schematic Diagram: Cogging torque can be eliminated by sinusoidal distribution of stator windings and/or magnetic flux density along the airgap [2]. Conventional small size SPM

TABLE I
CONVENTIONAL SPM MOTOR DESIGN PARAMETERS

Item	Unit	Value
Outer diameter of stator	mm	44
Inner diameter of stator	mm	25.5
Outer diameter of rotor	mm	25
Thickness of permanent magnet	mm	3.5
Airgap	mm	0.5
Statck length	mm	52
No. of poles	-	4
No. of slots	-	6

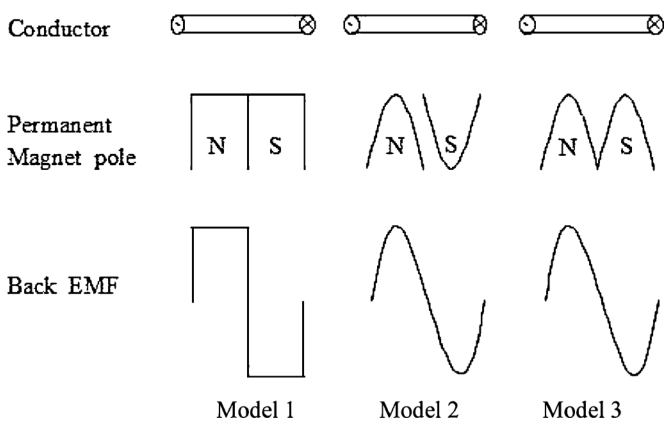

Fig. 2. Schematic diagram of SPM motor models and their back EMF generation.

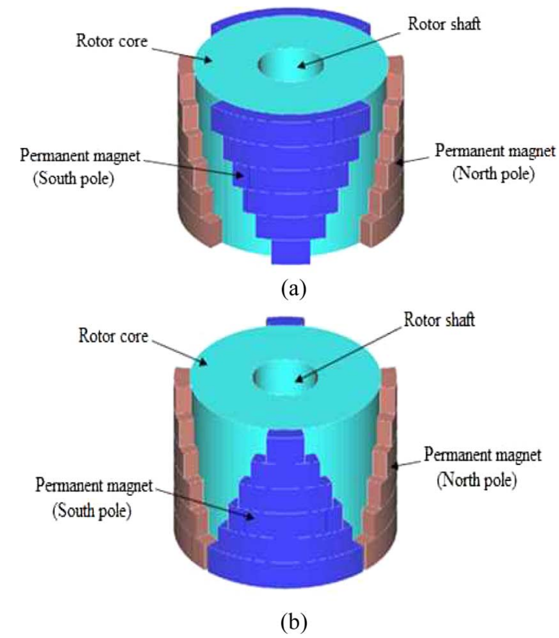

Fig. 3. PM structure of the proposed SPM motor models. (a) Model 2. (b) Model 3.

TABLE II
WINDING SPECIFICATION OF SPM MOTOR MODELS

Item	Unit	Model 1	Model 2	Model 3
Number of turns per coil	-	125	146	
Conductor diameter	mm	0.6	0.55	
Resistance per coil	Ω	1.9125	2.6584	
Current density	A/mm²	4.05	4.82	

motors have non-sinusoidal magnetic flux distribution due to the square shape of the PM poles, whereas, sinusoidal distribution of the stator winding is complex due to a fewer number of slots. Therefore, PM pole shape of SPM motor can be modified for sinusoidal magnetic flux distribution so as to generate the sinusoidal back EMF and eliminate the cogging torque. Fig. 2 illustrates the schematic diagram of conventional and proposed PM pole shape structure. Model 1 is the PM pole shape of conventional SPM motor, whereas Model 2 and Model 3 are novel PM pole shapes of the proposed SPM motor models. Both proposed models have sinusoidal PM pole shape in the axial rather than radial direction. Therefore the magnetic flux will be effectively sinusoidally distributed along the airgap. Thus, when the conductor cuts the sinusoidally distributed magnetic flux, sinusoidal back EMF will be generated.

2) Proposed Permanent Magnet Structure: The ideal PM pole shape proposed in the schematic diagram of Fig. 2, is clearly difficult to manufacture. Therefore, proposed PM pole shapes of Model 2 and Model 3 can be stacked is steps, as shown in Fig. 3. Though both proposed models are easier to manufacture and less expensive than the ideal proposed SPM motor models of the schematic diagram, still both proposed Model 2 and Model 3 are more difficult to manufacture and costly as compare to the conventional Model 1. For the large scale manufacturing, manufacturing cost of proposed SPM motor models can be reduced considerably, whereas rapid growth in the permanent magnet materials research may resolve the manufacturing issue in the near future. As the PM pole shape is not purely sinusoidal, the magnetic flux will not be purely sinusoidally distributed. Thus, small fluctuations in the back EMF are expected resulting in a small cogging torque.

III. CHARACTERISTICS ANALYSIS

A. Analysis Conditions

Although 3-D FEA consumes more time, it is utilized here due to the non-symmetrical PM pole shape of the proposed SPM motor models and to obtain the better accuracy results. The conventional Model 1 as well as proposed Model 2 and Model 3 have same main dimensions, except for the PM pole shape and its volume. Same back EMF is needed to supply the same excitation source for a reasonable comparative characteristic analysis of all SPM motor models. As both the proposed models contain less PM as compare to conventional Model 1, therefore less back EMF will be generated. Thus, to generate same back EMF, same magnetic flux linkages are required. Magnetic flux linkages are the product of magnetic flux and number of turns. Therefore, number of turns per phase is increased with the same proportionality as with the decrease in the magnetic flux of the proposed SPM motor models, to develop the same magnetic flux linkages and generate same back EMF for reasonable characteristic comparison of SPM motor models.

As the number of turns of proposed SPM motor models is increased, stator weight and volume will be increased. Thus, conductor diameter should be reduced to obtain the same stator weight and volume. Similarly, reducing the conductor diameter increases the current density, as shown in Table II.

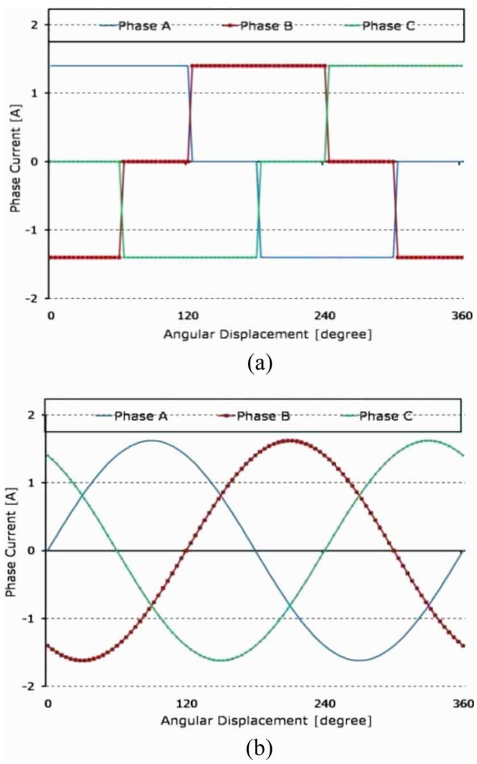

Fig. 4. Stator current excitation source. (a) Square current. (b) Sinusoidal current.

By definition, no excitation source is involved for the back EMF and cogging torque. Therefore, cogging torque along with back EMF is determined without any excitation source.

To determine the electromagnetic torque of SPM motor models, stator current excitation of 1.14 Arms and 120° phase shift is utilized, as shown in Fig. 4. Square and sinusoidal current excitation source as shown in Fig. 4(a) and (b), respectively are supplied separately, as to analyze the behavior of electromagnetic torque, on both current waveforms.

B. Analysis Results and Discussions

1) Back EMF Analysis: SPM motor models are analyzed at 5000 rpm without stator current excitation source in order to compare the back EMF of the SPM motor models. Proposed Model 2 and Model 3 show almost sinusoidal back EMF due to the sinusoidal magnetic flux distribution in the air gap, whereas conventional Model 1 shows a rectangular back EMF due to the rectangular magnetic flux distribution in the air gap, as shown in the Fig. 5. Small fluctuations in the sinusoidal nature of the back EMF of proposed models are due to the stacking structure of PM pole shape. Although peak value of proposed SPM motor models are higher than the conventional Model 1, all SPM motor models have almost same effective rms back EMF as shown in Table III, in order to obtain reasonable comparative characteristic analyses of SPM motor models.

2) Cogging Torque: Similar to Back EMF, cogging torque can be determined without supply of stator current excitation source. As conventional Model 1 has a square PM pole shape, it therefore contains high cogging torque due to the rectangular magnetic flux distribution in the airgap. Whereas, both proposed models Model 2 and Model 3 have almost sinusoidal but stacked PM pole shape, cogging torque is almost eliminated due to almost sinusoidal magnetic flux distribution in the airgap. Cogging torque of SPM motor models is shown in the Fig. 6. Although cogging torque is almost eliminated in both the proposed SPM motor models, it can be fully eliminated by exact sinusoidal distribution of magnetic flux in the airgap. As both north and south poles of Model 2 are alike with the positive and negative half sinusoidal cycle, thus Model 2 has lesser cogging torque than the Model 3, as shown in Table III.

3) Electromagnetic Torque: SPM motor models are analyzed with both square as well as sinusoidal current excitation source of 1.14 Arms, respectively. When square current excitation is provided, each SPM motor model contains torque ripples, but the proposed Model 2 and Model 3 have much less torque ripple

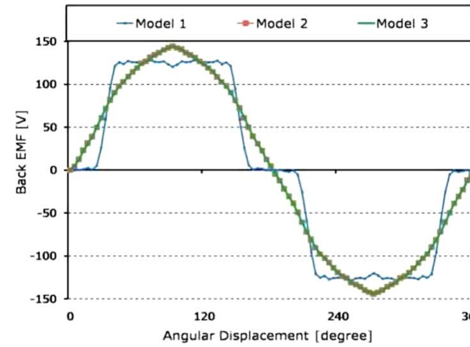

Fig. 5. Back EMF waveform of phase A of SPM motor models.

TABLE III
ANALYSIS RESULTS OF SPM MOTOR MODELS

Items	Unit	Model 1		Model 2		Model 3	
Magnetic volume	cm³	26		19.827			
Rotor volume	cm³	94.4		88.227			
Back EMF	Vrms	99.43		99.16		99.14	
Cogging torque	Nm	0.4964		0.0859		0.0894	
Current waveform	-	Square	Sinu-soidal	Square	Sinu-soidal	Square	Sinu-soidal
Torque	Nm	0.5102	0.6317	0.5446	0.6503	0.5446	0.6503
Torque ripple	%	148.06	86.63	53.78	14.55	53.53	14.73
TRV	Nm/cm³	0.0054	0.0067	0.0062	0.0074	0.0062	0.0074
Output power	W	267.28	330.9	285.25	340.48	285.27	340.49
Losses	W	36.509	44.68	32.32	35.59	33.43	37.02
Efficiency	%	87.98	88.1	89.82	90.54	89.51	90.19

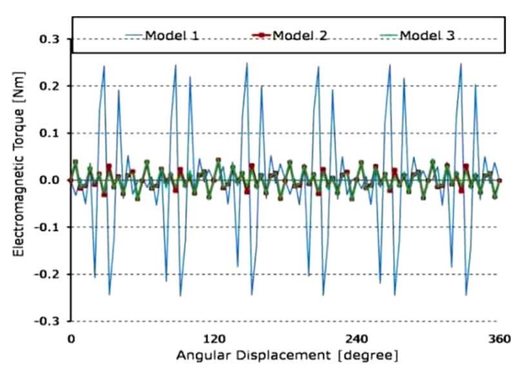

Fig. 6. Cogging torque of SPM motor models.

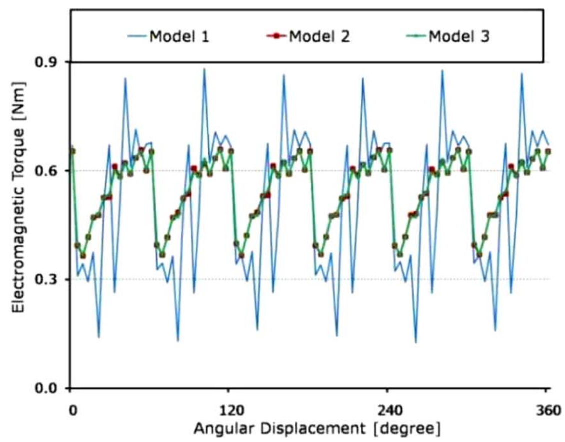

Fig. 7. Electromagnetic torque when square current waveform excitation is supplied.

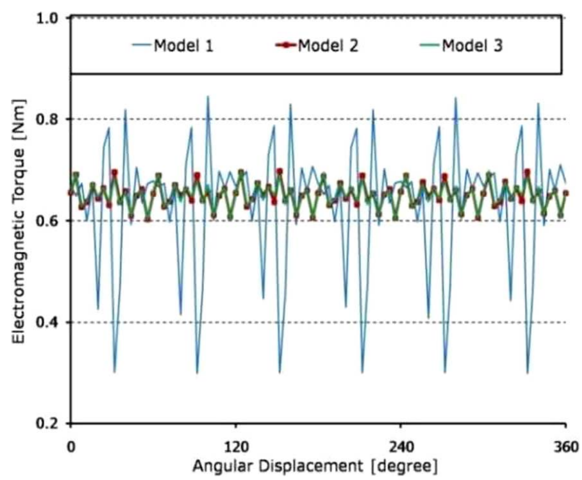

Fig. 8. Electromagnetic torque when sinusoidal current waveform excitation is supplied.

and better linearity than the conventional Model 1, as shown in Fig. 7.

Although torque ripples are reduced in both the proposed models, reduction in the torque ripples is much less as compared to the reduction of cogging torque in the proposed models, as shown in Table III.

When sinusoidal current excitation of 1.14 Arms is provided, torque ripples are highly reduced in the proposed models as compared to the conventional SPM motor Model 1, due to the coherence of sinusoidal current excitation source with the generated sinusoidal back EMF. Fig. 8 shows the better linearity and average electromagnetic torque when sinusoidal current excitation is provided.

PM volume as well as weight is reduced in the proposed SPM motor models, whereas electromagnetic torque is increased, therefore torque per rotor volume (TRV) of the proposed SPM motors is better than the conventional SPM motor Model 1 at both square as well as sinusoidal current excitation source, as shown in Table III.

4) Efficiency: In order to generate the same back EMF with the conventional SPM motor, the number of turns per phase of the proposed models was increased. Therefore, the conductor diameter is reduced for the reasonable comparison of SPM motor models, considering slot space factor. Although copper losses of proposed SPM motor models are increased due to an increase in the resistance of coil, core losses are reduced due to less PM volume and lower magnetic flux density, as compared with the conventional SPM motor Model 1. Therefore total losses are reduced in the proposed SPM motor models at both square and sinusoidal current excitation, as shown in Table III.

Output power can be determined, as in (1)

$$P_{\text{out}} = 2\pi n T_{\text{avg}} \tag{1}$$

where, P_{out} is output power, n is speed in rpm and T_{avg} is electromagnetic torque of SPM motor.

Efficiency of SPM motor can be determined, as in (2)

$$\eta = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{losses}}} \tag{2}$$

where, η is the efficiency of SPM motor and P_{losses} is the total losses of SPM motor.

Due to more output power and less total losses, efficiency of proposed models is better than conventional Model 1, as shown in Table III. Similarly, proposed models shows better performance when sinusoidal current excitation source is supplied as compare to square current excitation.

Model 2 shows slightly better efficiency than the Model 3, as it has lesser total losses, as shown in Table III.

IV. Conclusion

This paper has presented a novel PM pole shape of SPM motor for realizing sinusoidal back EMF and obtaining linear electromagnetic torque generation by minimizing the torque pulsations. Although cogging torque is almost eliminated in the proposed SPM motor models as compared to the conventional Model 1, it is not fully eliminated due to the stacking structure of permanent magnets.

Sinusoidal current excitation gives better linearity and average electromagnetic torque as compared to a square wave current excitation source, due to the coherence of both sinusoidal current excitation sources and the generated sinusoidal magnetic flux distribution. Torque ripples are highly reduced in the proposed models especially in Model 3.

Proposed models Model 2 and Model 3 show better characteristics than the conventional Model 1, as it contains less PM volume, generates sinusoidal back EMF, has linear and better electromagnetic torque and higher TRV.

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