Novel 4/4 Stator/Rotor Single-Phase Asymmetric-Stator-Pole Doubly Salient Machine with Permanent Magnets on Stator Teeth

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Introduction

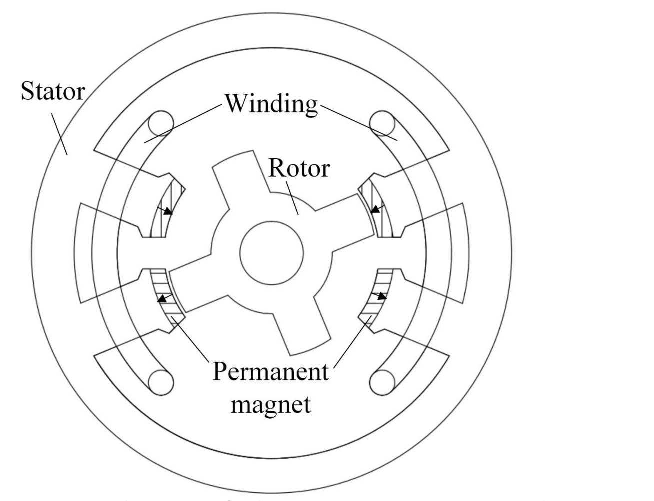
Electric tools have been widely used in industrial applications and human livings, and would be expected to get great increase in near future due to the coming of aging society. It indicates that doubly salient permanent magnet machine (DSPMM) would be one good candidate for electric tools due to its advantages over high torque density, high efficiency, high reliability, low maintenance, etc. However, the traditional single-phase DSPMM up to now has poor starting capability, relatively low torque density and large torque ripple, which limits its wide application in electric tools. Thus, one novel 4/4 stator/rotor single-phase asymmetric-stator-pole doubly salient machine with permanent magnets on stator teeth is proposed and investigated comprehensively in this paper.

Topology and Operation Principle

As shown by the topology, the stator poles are distributed non-uniformly along the circumference. The angle between the two adjacent stator poles is 45 degrees. Full-pitched armature windings are used and the rotor is similar to that of switched reluctance machine (SRM).

The instantaneous torque produced by the proposed machine can be calculated by

$$T = i\frac{\partial \psi_{pm}}{\partial \theta} + \frac{1}{2}i^2\frac{\partial L}{\partial \theta} - \frac{\partial W_{pm}}{\partial \theta} = T_{pm} + T_r - T_{cog}$$



Topology of the proposed machine

To analyze the harmonics of no-load air-gap flux density, the idealized magneto motive force (MMF) and air-gap permeance curves are given, as illustrated by the following figures.

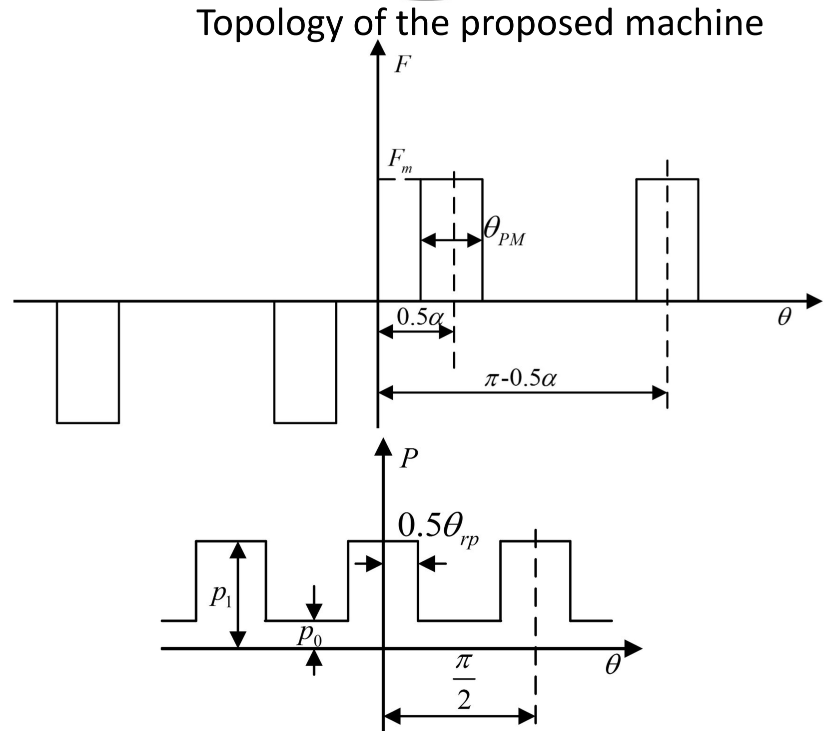
The corresponding expressions for the MMF and air-gap permeance are shown by

$$\begin{cases} F(\theta) = \dfrac{4F_m}{\pi}\displaystyle\sum_{i=1,3,5\cdots}^{\infty} K_i \sin(i\theta) \\ K_i = \dfrac{\cos\frac{i}{2}(\alpha - \theta_{PM}) - \cos\frac{i}{2}(\alpha + \theta_{PM})}{i} \end{cases} \qquad \begin{cases} P(\theta,t) = p_0' + \dfrac{2(p_1 - p_0)}{\pi}\displaystyle\sum_{j=1,2,3,\cdots}^{\infty} M_j \cos\left[4j(\theta - \omega_r t - \theta_0)\right] \\ M_j = \dfrac{\sin(2j\theta_{rp})}{j} \end{cases}$$

Thus the expression of no-load air-gap flux density can be calculated by

$$\begin{aligned} B(\theta,t) &= F(\theta)P(\theta,t) \\ &= \frac{4F_m p_0'}{\pi}\sum_{i=1,3,5\cdots}^{\infty} K_i \sin(i\theta) \\ &\quad + \frac{4F_m(p_1 - p_0)}{\pi^2}\sum_{i=1,3,5\cdots}^{\infty}\sum_{\cdots}^{\infty} K_i M_j\left[\sin(\alpha_1) + \sin(\alpha_2)\right] \end{aligned} \qquad \begin{cases} \alpha_1 = i\theta + 4j(\theta - \omega_r t - \theta_0) = (i+4j)\left[\theta - \dfrac{4j(\omega_r t - \theta_0)}{(i+4j)}\right] \\ \alpha_2 = i\theta - 4j(\theta - \omega_r t - \theta_0) = (i-4j)\left[\theta + \dfrac{4j(\omega_r t - \theta_0)}{(i-4j)}\right] \end{cases}$$

The no-load air-gap flux density only contains odd harmonics, which can be divided into stationary and rotational components. Furthermore, the angular velocity of rotational component is only related to the harmonic frequency of air-gap permeance.



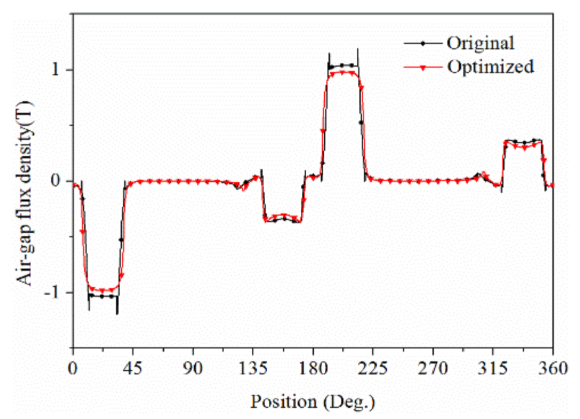
Idealized MMF and air-gap permeance

Performance Analysis

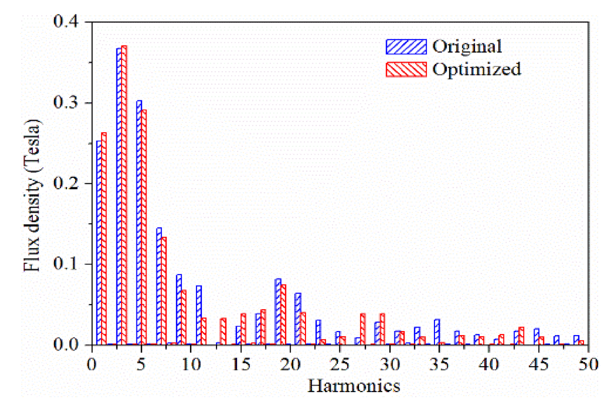
The no-load air-gap flux density curves and harmonic analysis for the original and optimized machine are shown by the following figures. It is known that the MMF produced by PMs only contains odd harmonics. Thus, through the modulation of rotor permeance, the no-load air-gap flux density also contains only the odd harmonics.

The average electromagnetic torque for the original and optimized topology is 0.731 and 0.686 Nm, respectively. Thus, the average torque is reduced 6.2% after the optimization. Considering that the volume of PMs is reduced from 4266 to 3132 mm3, the average torque produced by per unit PMs is increased by 27.0%. Besides, the torque ripple can also be reduced 15.2% after the refinement.

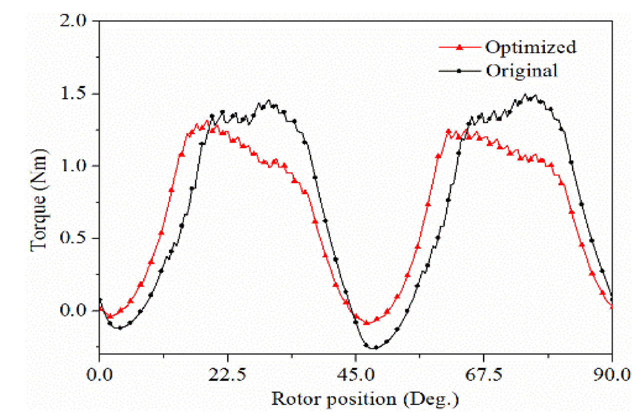
It is known that the PM eddy-current loss is reduced 16.4% compared with that of original one, which is caused by the reduction of PM material. Thus, the total loss is decreased from 561 to 525 W and the efficiency is improved from 77.33% to 77.38%.



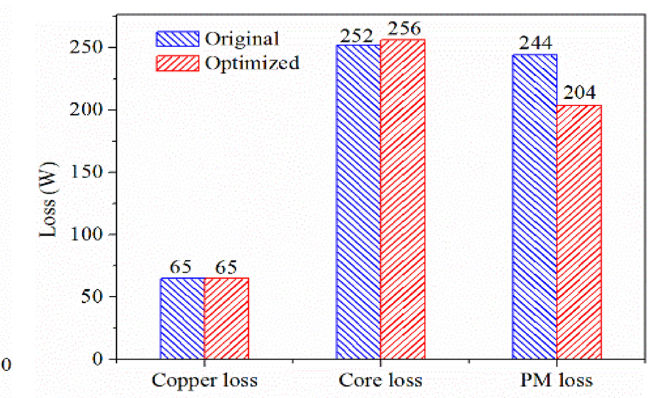
No-load air-gap flux density



FFT of no-load air-gap flux density



Electromagnetic torque



Losses

Conclusion

One novel 4/4 stator/rotor single-phase asymmetric-stator-pole doubly salient machine PMs on stator teeth is proposed, optimized and analyzed in this paper. It indicates that the optimized topology can enjoy the advantages as follows.

- higher average torque (produced by per unit PMs), increased 27.0%
- Higher efficiency, improved 0.05%
- Lower torque ripple, reduced 15.2%

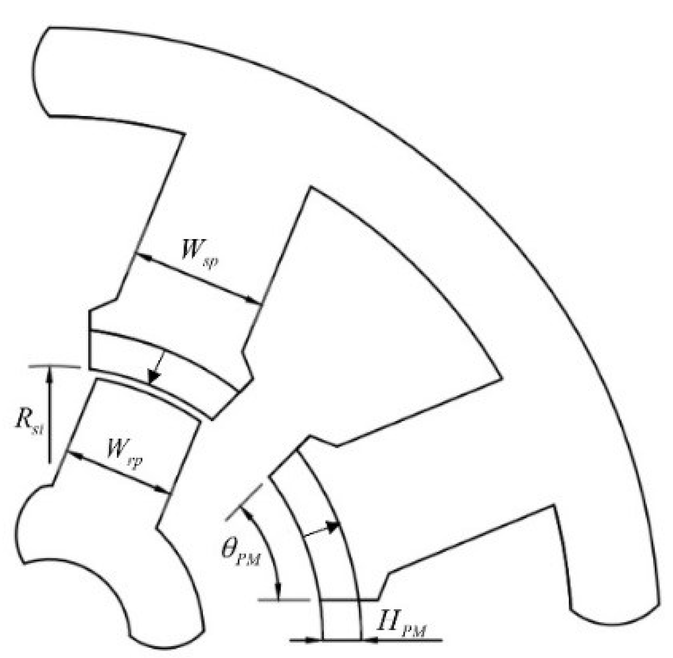
Electromagnetic Optimization

Based on the theory of motor design, one prototype for the proposed machine is designed and the detailed parameters are given in the following table.

Several structure parameters and one objective function are built to refine the proposed machine.

$$f(\mathrm{x}) = a\frac{T_N}{T_{avg}} + b\frac{T_{pk2pk}}{T_{avg}} + c(0.75 - \eta)$$

Taguchi algorithm is used to conduct the optimization, the levels for each structure parameters are given. Thus, one orthogonal array with five factors and four levels is designed.



Optimization parameters

Main design specifications

Parameters	Values	Unit
Stator outer radius	76/2	mm
Stack length	45	mm
Air-gap length	0.4	mm
Rotor outer radius	19	mm
Width of PM in Degrees	28	degree
Height of PM	2.5	mm
Width of stator pole	7	mm
Width of rotor pole	7	mm
Height of stator yoke	4.5	mm
Height of rotor pole	6.5	mm
Rated power	1.5	kW
Rated speed	25000	rpm

After the optimization, the effect of each factor on objective function and the optimal structure parameters are shown in the tables. It is known that the stator inner radius, width of rotor pole and width of rotor pole have the highest impact on the objective function.

Levels of the designed variables

Design variable		Level 1	Level 2	Level 3	Level 4
A:	R_{si}	19	20	21	22
B:	W_{sp}	6.5	6.8	7.1	7.5
C:	W_{rp}	6.5	6.8	7.1	7.5
D:	H_{PM}	1.6	1.9	2.2	2.5
E:	θ_{PM}	27.5	28	28.5	29

Effect of every variable on objective function

Factor	Objective function	
	SS	Factor effects (%)
A	0.3440	32.38
B	0.0634	5.96
C	0.3852	36.26
D	0.1553	14.62
E	0.1145	10.78
Total	1.0624	100

Optimal structure parameters

Symbols	Description	Value	Unit
R_{si}	Stator inner radius	17	mm
W_{sp}	Width of stator pole	7.12	mm
W_{rp}	Width of rotor pole	7.8	mm
H_{PM}	Height of PMs	1.92	mm
θ_{PM}	Width of PMs in degrees	30.6	degree

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