A Novel Doubly-Fed Flux-Switching Permanent Magnet Machine With Armature Windings Wound on Both Stator Poles and Rotor Teeth

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Overview

Introduction

- The flux-switching PM (FSPM) machine is a type of stator-PM machines.
- In stator-PM machines, all PM materials are located in the stator while the rotor is simply iron core with salient poles.
- The PM machines exhibit the merits of high efficiency and high torque density.
- The fault-tolerant capability of FSPM machines is of vital importance for the aerospace applications.

Introduction

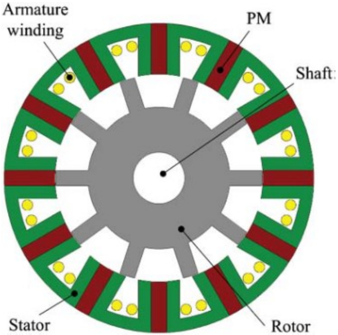

Figure: Structure of FSPM machine

- In the DF-FSPM machine, armature windings are wound on both stator poles and rotor teeth.
- The machine topology is presented with reference to a 12-stator-pole/10-rotor-tooth DF-FSPM machine.

Machine Topology

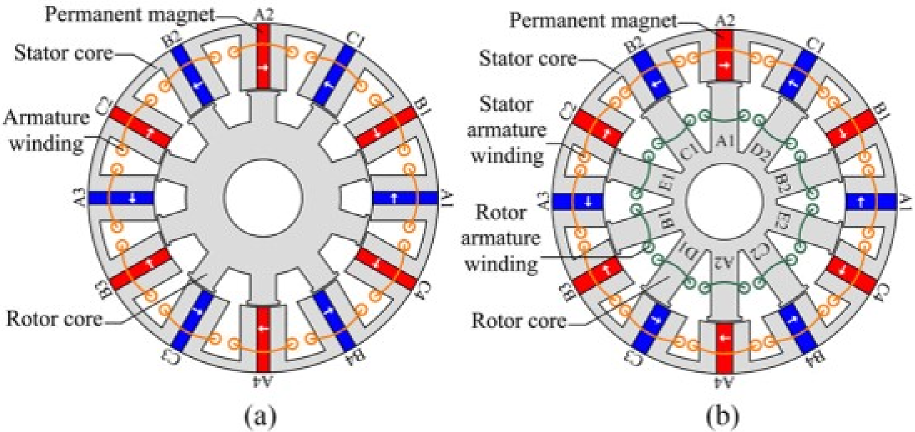

Figure: Illustration of machine topologies. (a) Conventional FSPM machine. (b) Presented DF-FSPM machine

Operating Principle

Stator-armature Machine Part

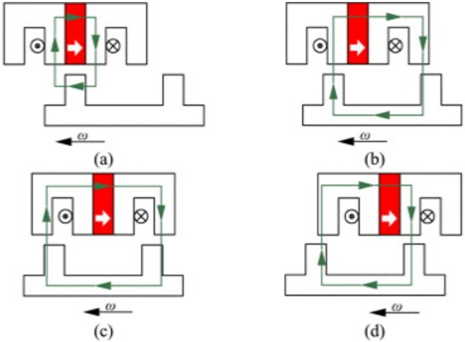

Figure: (a) Zero stator coil flux linkage. (b) Positive maximum stator coil flux linkage. (c) Zero stator coil flux linkage. (d) Negative maximum stator coil flux linkage.

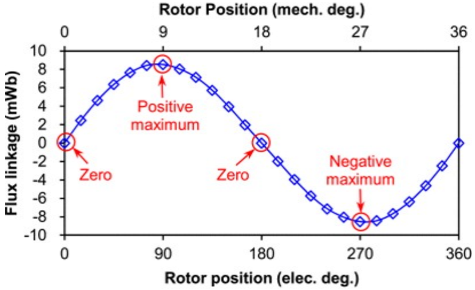

Figure: Flux linkage waveform of a single stator coil

Operating Principle

Rotor-armature Machine Part

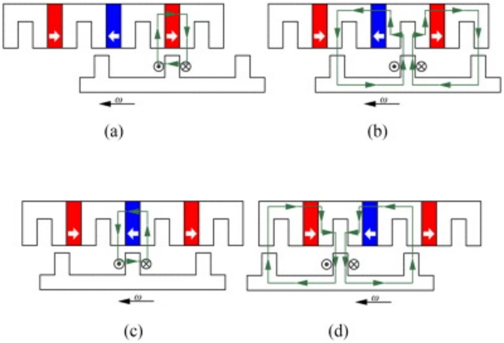

Figure: (a) Zero stator coil flux linkage. (b) Positive maximum stator coil flux linkage. (c) Zero stator coil flux linkage. (d) Negative maximum stator coil flux linkage.

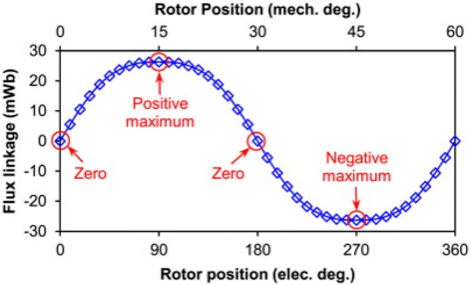

Figure: Flux linkage waveform of a single rotor coil

Operating Principle

dq-axis of Stator-armature Machine Part

- The d-axis of the stator-armature machine part is 9 mech. deg. shifted from the midline of the rotor tooth.

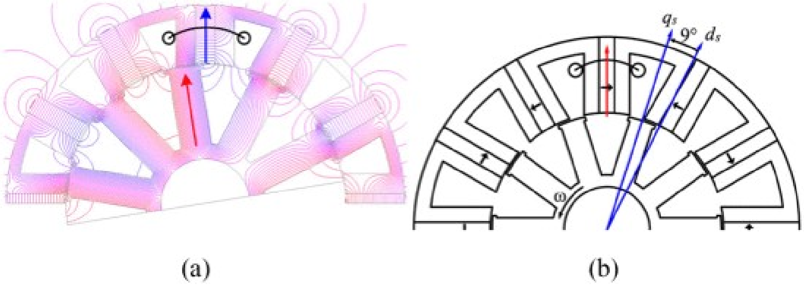

Figure: (a) Open-circuit flux distribution, rotor position = 9 mech. deg. (b) dq-axis of stator-armature machine part.

Operating Principle

dq-axis of Rotor-armature Machine Part

- The midline of the stator slot is defined as the d-axis of the rotor-armature machine part.

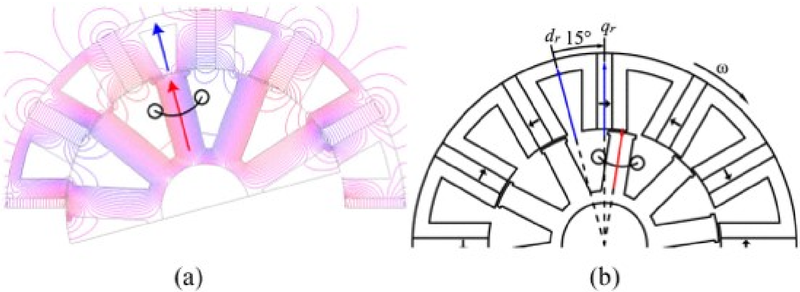

Figure: (a) Open-circuit flux distribution, rotor position = 15 mech. deg. (b) dq-axis of rotor armature machine part.

Operating Principle

The fundamental electrical frequency of stator flux linkages	$f_s = N_r n_r / 60$
The fundamental electrical frequency of rotor flux linkages	$f_r = (N_s/2) n_r / 60$

Table: Fundamental frequency flux linkages

N_r - number of rotor teeth
N_s- number of stator poles
n_r - rotating speed of the rotor

Operating Principle

Coil-EMF Vectors

The electrical angular distance between two adjacent stator coils	$\alpha_{es} = 360°.N_r/N_s$
The electrical angular distance between the two adjacent rotor coils	$\alpha_{er} = 360°.(N_s/2)/N_r$

Table: Angular distance between coils

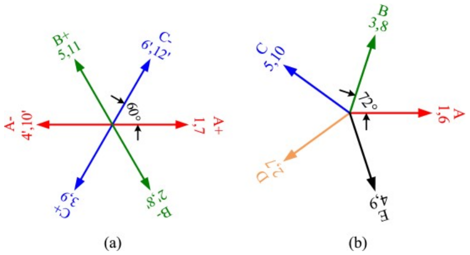

Figure: (a) Stator coil-EMF vectors. (b) Rotor coil-EMF vectors.

Electromagnetic Performance

Induced Voltage

- The PM-induced stator phase voltages of DF-FSPM and FSPM machines are sinusoidal.

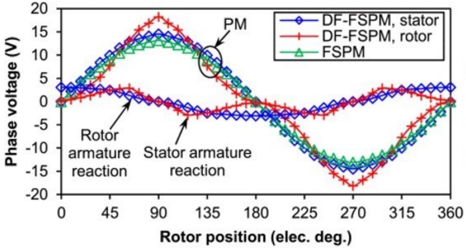

Figure: Phase voltage waveforms of DF-FSPM and FSPM machines.

- In DF-FSPM machines, the stator and rotor armature reaction fluxes are linked by the rotor and stator coils.

Electromagnetic Performance

Inductance

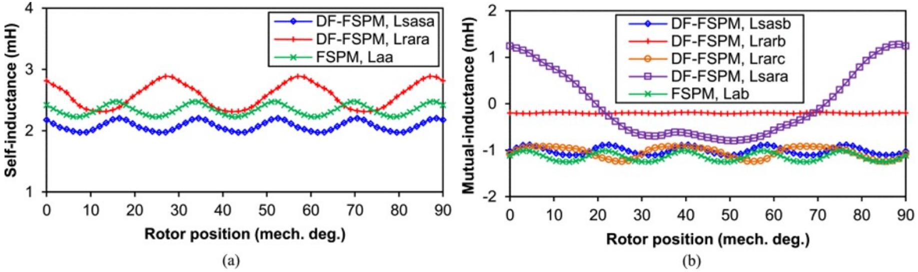

Figure: Inductances of DF-FSPM and FSPM machines under full load condition. (a) Self-inductance. (b) Mutual inductance.

L_{sasa} - stator self-inductance of the DF-FSPM machine
L_{aa} - stator self-inductance of the FSPM machine
L_{sasb} - stator mutual inductance of the DF-FSPM machine
L_{ab} - stator mutual inductance of the FSPM machine
L_{sara} - mutual inductance between the stator and rotor phases

Electromagnetic Performance

Cogging Torque

- It is the torque due to the interaction between the permanent magnets of the stator and the rotor teeth of the PM machine.
- The magnet arc of the optimized DF-FSPM machine is much greater than the FSPM machine.

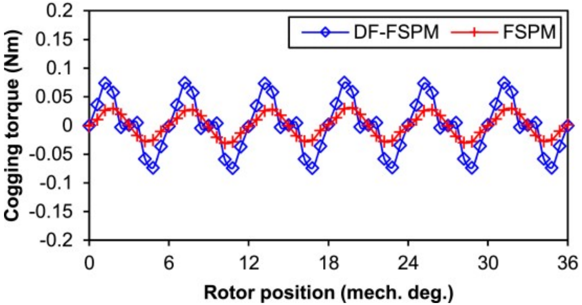

Figure: Cogging torque of DF-FSPM and FSPM machines.

Electromagnetic Performance

Torque Capability

- The effective slot area of the DF-FSPM machine is significantly improved by about 66% compared to the FSPM machine.

Parameter	DF-FSPM	FSPM
Average torque (Nm)	4.22	2.88
Average torque per magnet volume (kNm/m^3)	245.4	175.8
Peak to peak torque ripple (%)	4.4	3.0

Table: Electromagnetic Torque Comparison Under Full-Load Condition

- The torque ripple is increased due to large cogging torque.

Electromagnetic Performance

Torque Capability

- Under the fault-tolerant operation, the fault armature winding is cut off and the torque is produced by the healthy armature winding.

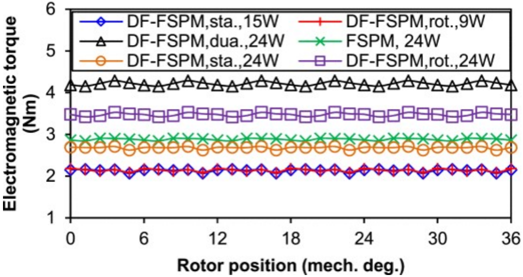

Figure: Electromagnetic torque waveforms

sta. - stator
rot. - rotor
dua. - dual armature currents supply

Electromagnetic Performance

Torque Capability

- The interaction of stator and rotor armature reaction fields of the DF-FSPM machine can produce electromagnetic torque,

$$T_{sr} = \underbrace{T(I_s = 2.98A, I_r = 1.78A)}_{\text{torque due to armature reaction fields}} - \underbrace{T(I_s = 0A, I_r = 1.78A)}_{\text{rotor reluctance torque}} - \underbrace{T(I_s = 2.98A, I_r = 0A)}_{\text{stator reluctance torque}}$$

- T_{sr} is zero when the stator and rotor current angles are equal.
- T_{sr} is positive if the stator current angle is larger than the rotor current angle.

Electromagnetic Performance

Torque Capability

- The maximum total torque of the DF-FSPM machine is achieved when both the stator and rotor current angles are 0 elec. deg.

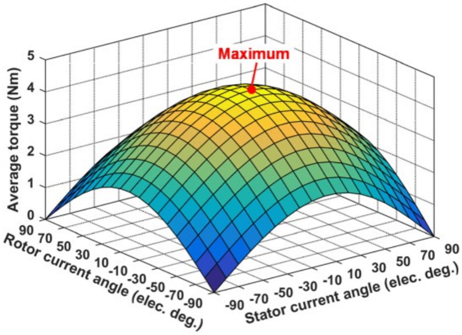

Figure: Variation of total average torque with stator and rotor current angles of the DF-FSPM machine.

Electromagnetic Performance

Flux Weakening Capability

- DF-FSPM machine exhibits higher average torque in the constant torque region.
- Flux weakening region of the FSPM machine is wider than that of the DF-FSPM machine.

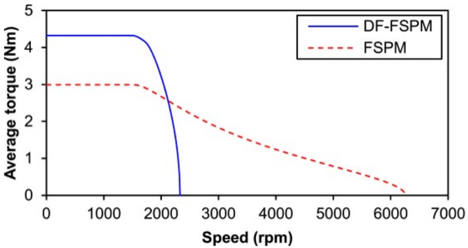

Figure: Torque–speed characteristics of DF-FSPM and FSPM machines.

- The maximum speeds of DF-FSPM and FSPM machines are 2320 r/min and 6250 r/min, respectively.

Electromagnetic Performance

Efficiency and Power Factor

	DF-FSPM			FSPM		
Parameter	Stator	Rotor	Total	Stator	Rotor	Total
Core loss (W)	0.8	1.1	1.9	0.9	0.7	1.6
Copper loss (W)	15	9	24	24	0	24
Efficiency (%)	-	-	87.2	-	-	82.5
Power factor	0.95	0.99	-	-	-	0.91

Table: Comparison of Efficiency and Power Factor

- The DF-FSPM machine has higher efficiency benefiting from its increased torque density.
- Both the stator and rotor parts of DF-FSPM exhibits high power factor.

Experimental Validation

Prototype Machine

- A 3-stator-phase/5-rotor-phase and 12-stator-pole/10-rotor-tooth DF-FSPM machine is manufactured.
- A 0.5 mm iron bridge is employed to connect the individual stator iron segments.

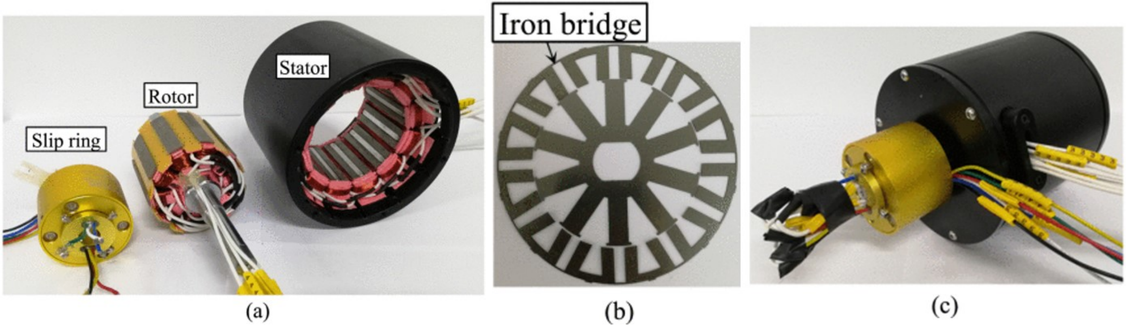

Figure: Prototype machine. (a) Machine components. (b) Laminations. (c) Assembled machine.

Experimental Validation

Back EMF

- The measured phase back EMFs are slightly smaller than the two-dimensional (2-D) FE predicted ones.

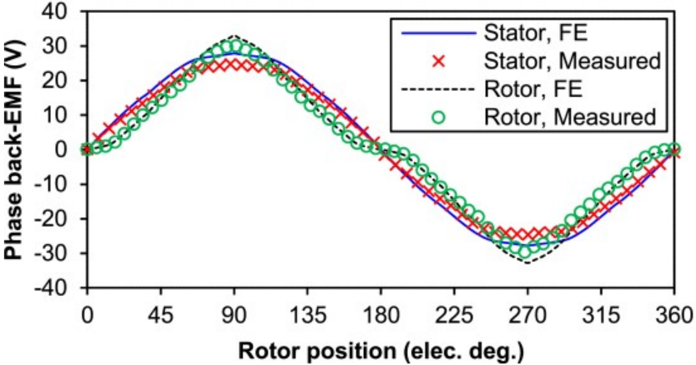

Figure: Comparison of measured and FE predicted phase back EMF waveforms at 400 r/min.

Experimental Validation

Static Torque

- The measured static torque is obtained by rotating the rotor when the phase currents are constant.

Comparison of measured and FE predicted static torque waveforms.

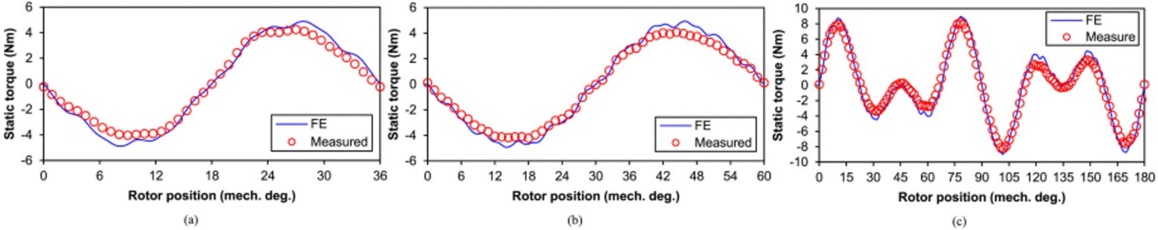

Figure: (a) Only stator current excitation.(b) Only rotor current excitation.(c) Dual excitation.

Conclusion

- A novel DF-FSPM machine was presented, in which the armature windings were wound on the stator poles and rotor teeth.
- The DF-FSPM machine exhibited about 46.5% higher torque density due to better utilization of inner space.
- Its torque per magnet volume was also improved by about 39.6%.
- The efficiency and power factor of the DF-FSPM machine were higher than those of the FSPM machine.

References

- L. Wu, J. Zhu and Y. Fang, "A Novel Doubly-Fed Flux-Switching Permanent Magnet Machine With Armature Windings Wound on Both Stator Poles and Rotor Teeth," in IEEE Transactions on Industrial Electronics, vol. 67, no. 12, pp. 10223-10232, Dec. 2020.
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Thank You