Electromagnetic Performance Analysis of Less-rare-earth Stator-partitioned Multi-excitation Flux-switching Machine Considering Multi-operation Conditions

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Session: Wed-Af-Po3；Program I.D. number:1076

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Background

In recent years, the modulated PM motor based on magnetic gear principle has caught more and more attention in EV direct-drive applications. Like other rare-earth PM motors, the modulated PM machine also has high torque output capacity. However, due to the high prices of rare-earth PM materials and its instability supply, the manufacturing cost of various PM motors is increased obviously which becomes one of the factors limiting the mass production of EVs. Hence, various design or control methods have been investigated in rare-earth PM motors to reducing the usage of rare-earth PM materials.

Objectives

- Combined with the characteristics of EV traction motor, a new less-rare-earth double-stator modulated (LER-DSM) machine is proposed.
- Performance analysis of LER-DSM machine considering multi-operation conditions

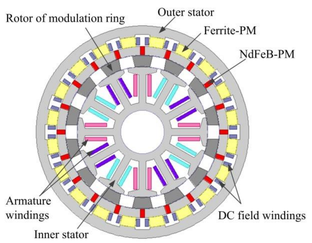
Conclusion

- A LER-DSM machine is proposed as the driving motor for EV application.
- In the LER-DSM machine, two types of excitation sources of rare-earth NdFeB-PM and non-rare-earth Ferrite-PM are skillfully integrated into a stator-partitioned modulated machine.
- The electromagnetic performances of the machine considering multi-operation conditions are analyzed and simulated in details.
- The FEM results combined theoretical analysis show that the proposed machine has advantages in multi-mode operation, which is suitable for EV driving applications.

LER-DSM machine structure

Structure

- LER-DSM machine consists of a rotor of modulation ring and a partitioned stator. The outer stator has two excitation sources of NdFeB-PMs and Ferrite-PMs which are arranged in parallel.
- Auxiliary DC field windings embrace the Ferrite-PMs which can protect the low-energy Ferrite-PM form the irreversible demagnetization.
- Inner stator only accommodates the armature windings. Rotor of modulation ring has 14 steel pieces located between the outer stator and inner stator.



Operating principle & Design parameters

Parameters of the Moter

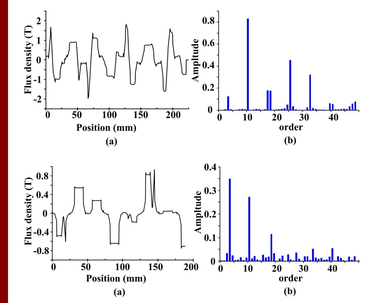
Parameters	data
Number of steel pole-pieces in rotor	15
Pole-pair number of PMs in outer stator	11
Pole-pair number of armature winding in inner stator	4
Gear ratio	3.5
number of phase	3
Outer stator outer diameter	196mm
Rotor outer diameter	141mm
Air-gap (inner and outer)	0.5mm
Core stack length	70mm
NdFeB-PM	4mm*8mm
Ferrite-PM	9mm*9deg
Rated speed	1250rpm
Number of turns per phase winding	180

- Operating principle of LER-DSM machine is based on the air gap field modulation theory.

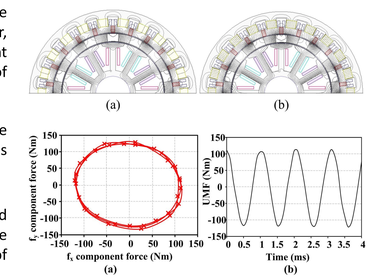
$$P_{is} = P_{eh} = |P_{os} - P_{my}|$$

P_{is}: Pole-pair number of armature winding in inner stator
P_{eh}: Pole-pair number of effective space harmonic
P_{os}: Pole-pair number of PMs in the outer stator
P_{mr}: Number of steel pole-pieces in the modulation rotor

Conventional analysis

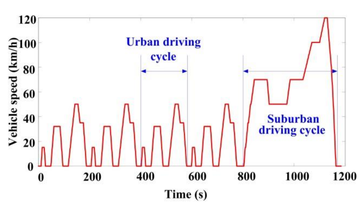


- The largest space harmonic component in the inner air gap is the 11rd one. After the modulation effect from the modulation rotor, The significant 4th space harmonic component will play an important role in the production of electromagnetic torque.
- NdFeB PM lead to the less magnetic leakage provided by ferrite PM, whilst both of the PMs have the better performance.
- UMF is reasonable with rational design of odd rotor pole number and double stator pole number, which may the extend lifetime of bearing and also reduce the vibration and noise.



Performance analysis considering Multi-operation Conditions

Multi-operation Conditions



- Typical New European Driving Cycles (NEDC) includes 4 urban driving cycles and 1 suburban driving cycle.
- Through the statistics, three main operation conditions in a NEDC is the normal speed cruise, followed by frequent start-stop and acceleration & deceleration.

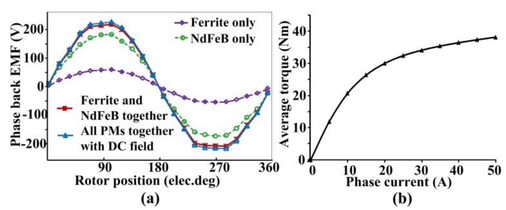
Performance analysis considering multi-operation conditions

- In terms of the normal speed cruise condition，the LER-DSM machine usually works at rated working condition.

Performances of Rated Condition

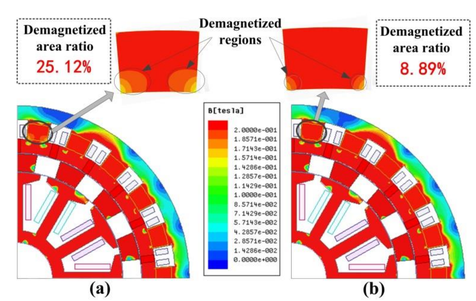
Performance	data
Output torque	25.6Nm
Torque ripple	19.3%
Core loss	73.1
Efficiency	92.7%
Power factor	0.714

- To meet the frequent start, acceleration or overloaded climbing, the flux-enhanced driving mode is preferred to obtain high torque. The output torque capability is the foremost requirement.

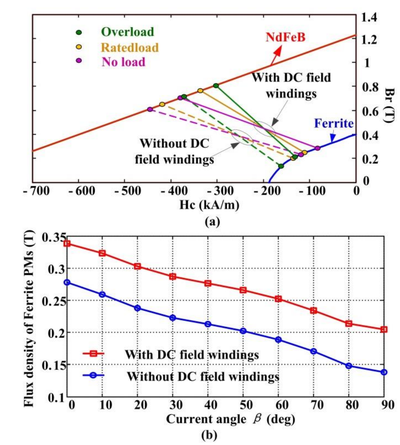


- With the multi-excitation working together, the motor have the better electromagnetic performance.
- Output torque can reach 40Nm.

- To realize the high-speed cruise, the flux-weakening driving mode is often necessary to realize the wide speed range.



- Demagnetization area is decreased from 25.12% without DC field current to 8.89% with the protection of DC field under overload condition.
- With DC field windings, Ferrite-PM operating points are increased above the knee point and even stay above 0.2T at β of 90º (the demagnetizing current reach its maximum).



Presented at 25th International Conference on Magnet Technology, 2017 Aug. 27 – Sep.1, Amsterdam, the Netherlands; Session: Wed-Af-Po3; Abstract I.D. number: #1076