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Optimization design of an interior permanent-magnet synchronous machine for a hybrid hydraulic excavator

Key words: Analysis, Design, Hybrid hydraulic excavator (HHE), Finite element method (FEM), Interior permanent-magnet (PM), PM synchronous machine (PMSM)

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Motivation/Main ideas

➢ Motivation

A design process for a PMSM in an HHE is presented, so as to improve the design efficiency and accuracy in a PMSM as well as the efficiency in an HHE.

➢ Main ideas

– Introduce special working conditions of excavators and analyze requirements of an electric machine for HHE applications.

– Combine analytical model and 2D FEM to design the electric machine.

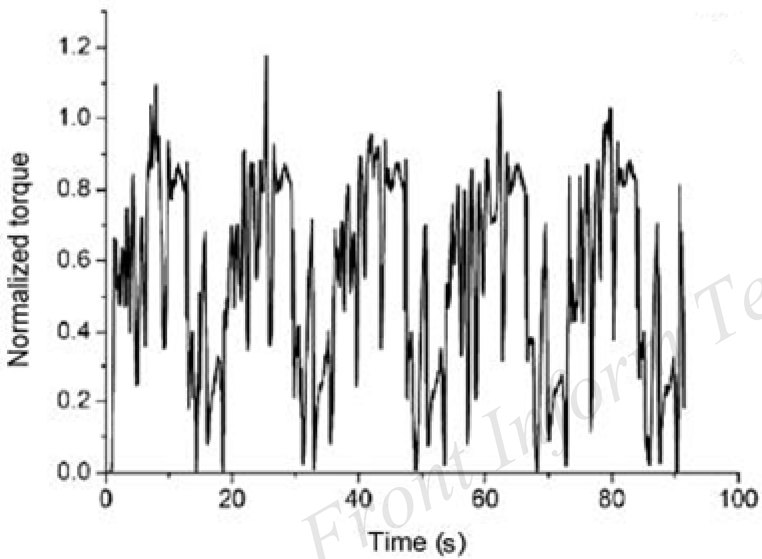
– Use an interior magnet structure and a disconnected-type silicon steel block to improve the torque density and reduce the rotor leakage. Employ the trapezoid PM and centrifugal rotor structure to improve the air gap flux density distribution.

Method (I)

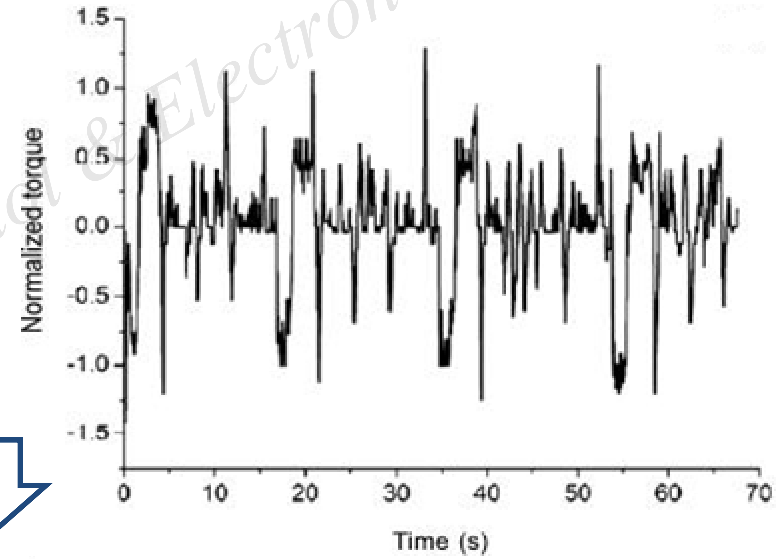
1. Working conditions of excavators & requirements of an electric machine for HHE applications

Working conditions of excavators

Normalized torque absorbed by pump



Normalized torque produced by PMSM



Requirements of electric machines

1. Two working modes: motor mode and generator mode
2. High torque density
3. Quick response
4. High efficiency

Method (II)

2. Design stage

Stage 1: The analytical model is employed to obtain the relationship between stator dimensions and flux density distributions. Based on the analytical model, a PSO is implemented to optimize parameters of the stator. The optimization target is to improve the PMSM efficiency.

Stage 2: FEM is used to design the rotor structure and obtain an air gap flux density, which is a fundamental component with the predesigned value in the stage of the stator design and a relative small harmonic distortion.

Harmonic distortion

$$H_{\mathrm{d}} = \frac{1}{B_1}\sqrt{\sum_{i=2}^{\infty} B_i}$$

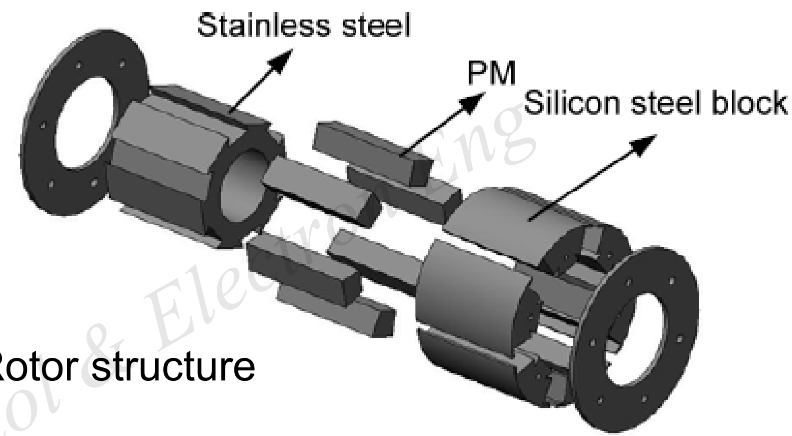
Method (III)

3. Rotor structure

1. Employ the interior NdFeB magnet structure to involve more important magnetic loading.

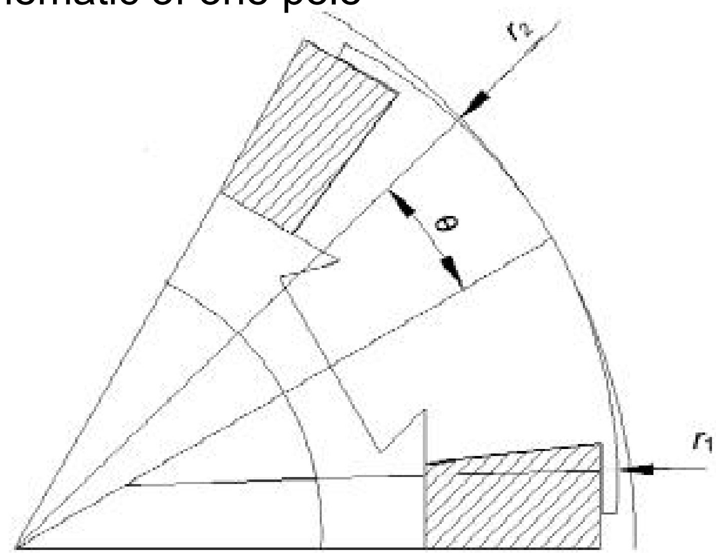
2. Adopt the disconnected type silicon steel block structure to reduce the rotor leakage.

3. Use the trapezoid PM and centrifugal rotor structure to improve the air gap flux density distribution.



Rotor structure

Schematic of one pole



Major results (I)

(a) (b)

Fig. 16 Fabricated PMSM

(a) Stator; (b) Rotor

Major results (II)

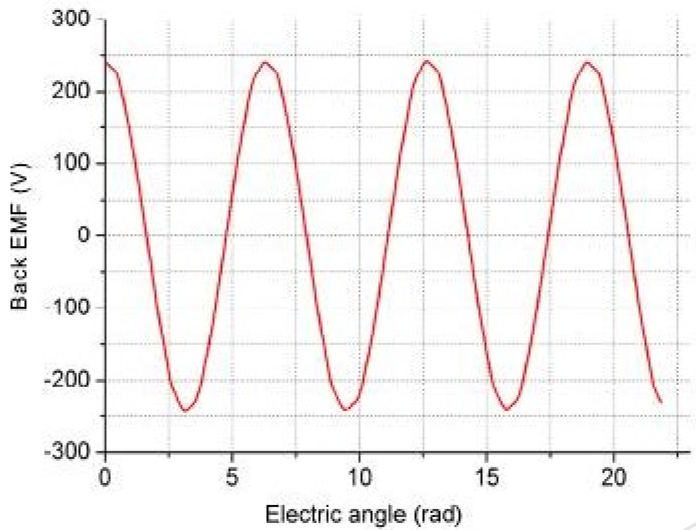


Fig. 18 Back EMF of PMSM

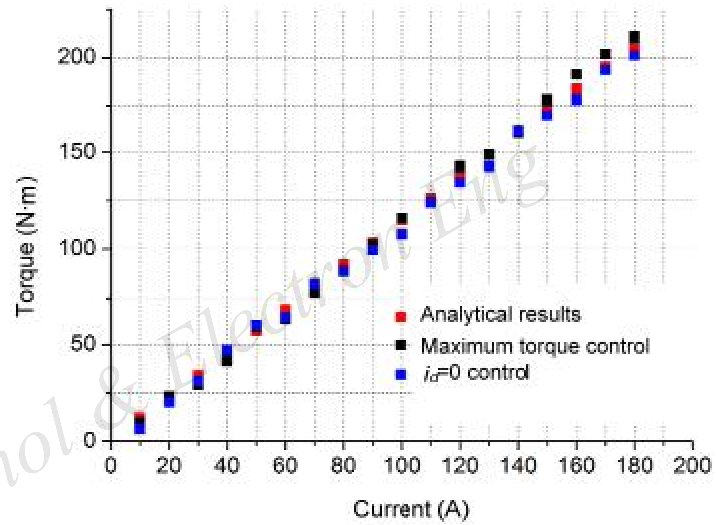


Fig. 19 PMSM torque output at different currents

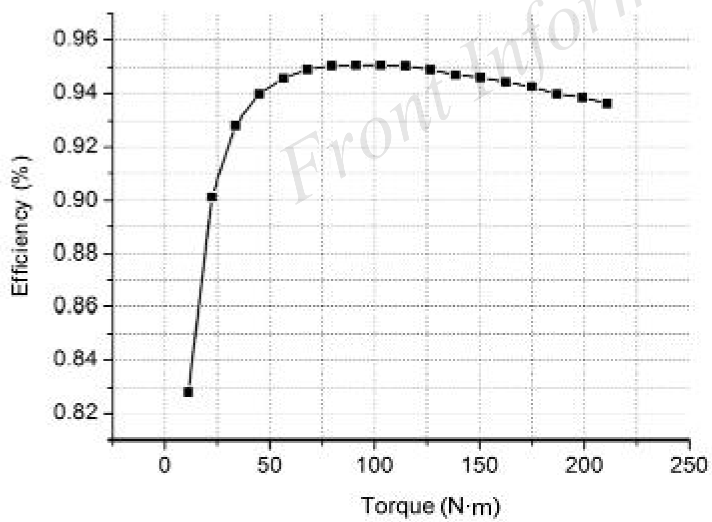


Fig. 20 Efficiency of the PMSM

Table 2 Comparison between the analytical and measured parameters

Parameter	Value	
	Analytical	Measured
Flux linkage (V·s)	0.255	0.249
Resistance (Ω)	0.0431	0.0417
Efficiency (%)	93.99	93.67

Conclusions

This paper introduces the design procedure of a PMSM for HHE applications. The design is based on the analysis of the requirements and working conditions of an HHE. We use an analytical model to design the stator of the PMSM, and FEM to design the rotor. The rotor uses an interior NdFeB magnet structure to involve more important magnetic loading. The disconnected-type silicon steel block structure is applied to reduce the rotor leakage. Furthermore, the trapezoid PM and centrifugal rotor structure are used to improve the air gap flux density distribution. The design of the PMSM has been validated by the experimental results. The PMSM is intended to be incorporated in a 20 t HHE.