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The 17th International Conference on Electrical Machines and Systems

Hangzhou, China   October 22-25, 2014

3rd Call for Papers

The 17th International Conference on Electrical Machines and Systems (ICEMS), organized by Zhejiang University, will be held in Hangzhou, China, on October 22-25, 2014. It is intended to provide a forum for researchers, professionals and engineers from all over the world to present their latest research and development achievements and to exchange information and experience in the areas of electrical machines and actuators, electric motor drives and systems, transformers, magnetics, power converters, system modeling and motion control, renewable energy systems, energy efficiency systems, transportation applications, manufacture and maintenance, materials, testing and standards, and other related areas.

All presented papers will be included in the conference proceedings and submitted to the databases of IEEEXplore and EI Compendex. Selected papers will be recommended to the IEEE Trans. Industry Applications and other SCI or EI-indexed journals.

Important dates:

Proposal of special sessions:	February 28, 2014
Submission of digests:	~~March 15, 2014~~ **4/20/2014**
Notification of acceptance:	~~May 1, 2014~~ **5/15/2014**
Submission of full papers:	July 31, 2014
Notification of acceptance:	September 15, 2014
Proposal of tutorials:	July 31, 2014

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DS1H5-7

Research on Self-Excited Initiation of a Medium-Voltage DC (MVDC) Multiphase Synchronous Generator-Rectifier System

Xinqiang Yi, Dong Wang, Yunjun Guo, Zhenzhong Su, Kun Wei, and Xiaofei Zhai
Naval University of Engineering, China

DS1H5-8

Analytical Calculation of Damper Winding Losses in Large Hydrogenerators

Yun Lu[1], Jianjun Liu[1, 2], Libing Zhou[1], and Huilin Kang[1]
[1]*Huazhong University of Science and Technology, China,* [2]*Dongfang Electric Machinery Co., Ltd., China*

DS1H5-9

Torque Ripple Reduction in Three-Stage Brushless Synchronous Motor Based on α-β-γ Filter

Peng Ma, Weiguo Liu, Shuai Mao, Jichang Peng, and Guangzhao Luo
Northwestern Polytechnical University, China

DS1H5-10

Influence of Manufacturing Tolerances on Cogging Torque of IPMSM for EPS Application

Yong-Beom Kim, Hae-Joong Kim, Kyung-Tae Jung, and Jung-Pyo Hong
Hanyang University, Korea

DS1H5-11

Stator Teeth Shape Design for Torque Ripple Reduction in Surface-Mounted Permanent Magnet Synchronous Motor

Kyung-Sik Seo[1], Yong-Jae Kim[2], and Sang-Yong Jung[1]
[1]*Sungkyunkwan University, Korea,* [2]*Chosun University, Korea*

DS1H5-12

New Permanent Magnet Synchronous Motor with Reduced Rare Earth Magnets

Akitoshi Yamada, and Ichiro Miki
Meiji University, Japan

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A Low-Cost Permanent Magnet Synchorous Motor with SMC and Ferrite PM

Chengcheng Liu[1], Jianguo Zhu[2], Youhua Wang[1], Gang Lei[2], Youguang Guo[2], and Xiaojing Liu[1]
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DS1H5-14

Comparison of Electrically Excited and Interior Permanent Magnet Machines for Hybrid Electric Vehicle Application

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University of Sheffield, UK

Influence of Manufacturing Tolerances on Cogging Torque of IPMSM for EPS Application

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Abstract — This paper examines a study of an unexpected cogging torque due to the manufacturing tolerances. During the manufacturing, to reduce the cogging torque, various design techniques can be chosen. However, some techniques, which are effective cogging torque reduction methods, can become ineffective. Also, if the manufacturing tolerances exist, they can cause an increase in the cogging torque magnitude.

In this paper, the influence of manufacturing defects on the cogging torque is analyzed. For this purpose, the finite-element (FE) analyses are utilized and validated by the experimental measurements.

I. Introduction

Nowadays an electric power steering (EPS) system is in the spotlight. The EPS system has advantages in fuel efficiency and high power density.

In the EPS system, the cogging torque of the electric motor is a very important factor due to driving comforts of the vehicle.

The cogging torque is an irregular torque in the motor and the force of the tangential direction that moves to a location where the magnetic energy is minimal. Regardless of the load current, the cogging torque is caused by the interaction between the permanent magnet and the slot [1].

In order to reduce the cogging torque, various design topologies can be chosen. For example, adoption of skewing, eccentricity and pole / slot combination can be regarded [2].

Although cogging torque reduction techniques minimize the cogging torque, the effectiveness of techniques could be limited or diminished by the manufacturing defects [3].

To study the influence of manufacturing tolerances on the cogging torque, a detailed theoretical and experimental study is carried out in this paper.

Also, this paper presents the analysis of the cogging torque of three different prototype motors. To measure the skew angle and the permanent magnet (PM) imperfection, the rotor surface flux density is measured by using a Gauss meter. To investigate the influence of the defective eccentricity on the interior permanent magnet synchronous motor (IPMSM), the variations in the cogging torque are compared when the defective eccentricity is applied to the IPMSM and the surface permanent magnet synchronous motor (SPMSM).

II. Prototype Machine

The analyzed prototype, Fig. 1 and Table I, is a fractional-slot 8-pole/12-slot interior PM (IPM) machine that is designed for an electric power steering system.

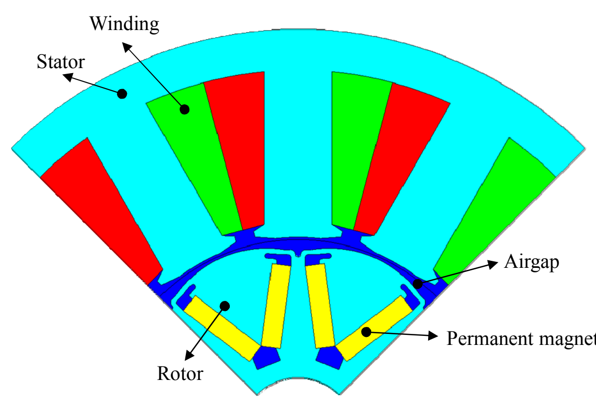

Fig. 1. Prototype machine

TABLE I
Major Parameters of Prototype Machine

Parameter		***Dimension***
Pole / Slot		8 / 12
Skew	Rotor step skew angle	3×5 mech. deg.
	Stator skew angle	15 mech. deg.
Magnet remanence		1.3 T
Magnet relative permeability		1.03
Stator yoke width		4.25 mm
Tooth width		7 mm
Stator outer diameter		84 mm
Axial length		45 mm
Airgap length		0.5 mm
Slot opening		2 mm

In this paper, three different prototype motors are used in the experiments and they are all the same except for the skewing.

Model 1 has a step-skewed rotor and Model 2 is a motor without skew. For Model 3, the stator skew is employed.

The cogging torque is the oscillatory torque of zero average value caused by the tendency of the rotor to line up with the stator in a particular direction where the permeance of the magnetic circuit "seen" by the magnets is maximized [4].

The period of cogging torque can be determined by expression (1) :

$$T = \frac{360°}{\mathrm{LCM}[2p, Z]} \quad (1)$$

where T is the period of cogging torque in mechanical degrees, $2p$ is the pole number, Z is the stator slot number, LCM is the lowest common multiple.

Theoretically, the cogging torque of motors should be well suppressed by using the cogging torque reduction techniques [5].

But many manufacturing defects could be behind such unexpected cogging torque, for example it can be due to:

a) Defective skewing

b) PM imperfection, e.g. placement, magnetization and/or strength

c) Tolerance of eccentricity

In the following analyses, the influence of such possible defects on the cogging torque is investigated.

III. Influence of Defective Skewing

A common approach for cogging torque minimization is by skewing. The skewing can be continuous or step-wise.

Model 1 is the machine having a step-skewed rotor.

For the 8-pole/12-slot combination, the least common multiple is 24, thus the cogging torque period is 15 mechanical degrees.

Theoretically, step skewing the rotor by 3 steps of 5 mechanical degrees for every step can nearly eliminate the cogging torque.

Since the step-skew angle is 5 mechanical degrees, the electrical angle difference between the cogging torque components is 120 electrical degrees.

The vector diagrams of cogging torque components are illustrated below.

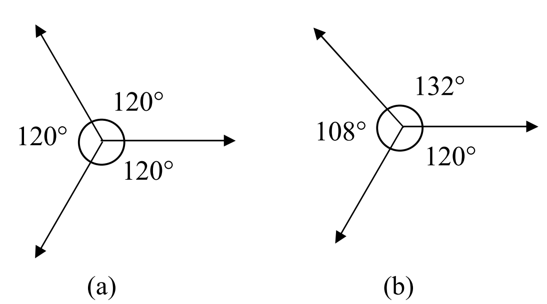

Fig. 2. Vector diagrams of cogging torque (a) balanced (b) unbalanced

Fig. 2 shows the balanced and the unbalanced cases of cogging torque components. In Fig. 2(a), it shows that the sum of the cogging torque components is zero. It means that cogging torque can theoretically be reduced to zero.

However, in Fig. 2(b), the skew angle between the first vector and the second vector is 132 electrical degrees, which is different from 120 electrical degrees.

Comparing with the balanced case, Fig. 2(b) shows that the sum of the cogging torque components is non-zero and implies that the cogging torque components exist.

IV. Influence of Nonuniform Magnetization Distribution

The magnets are parallel magnetized NdFeB having a remanence of 1.3 T.

In reality, due to the irregularities in magnetization pattern, the PM imperfection increases the cogging torque magnitude and generates low order cogging torque components.

A. Influence of axially nonuniform magnetization distribution

To investigate the effect of axially nonuniform magnetization distribution, the remanence per step is differently applied. The remanence of the leading piece and the lagging piece is 1.3 T while that of the centre piece is 1.35 T.

It should be assumed that the rotor rotates at 1 rps. In this case, if 1 Hz is the fundamental frequency, the frequency of the cogging torque components will be 24 Hz.

Thus, in the following analyses, the 24 Hz is assumed to be the frequency of the cogging torque components.

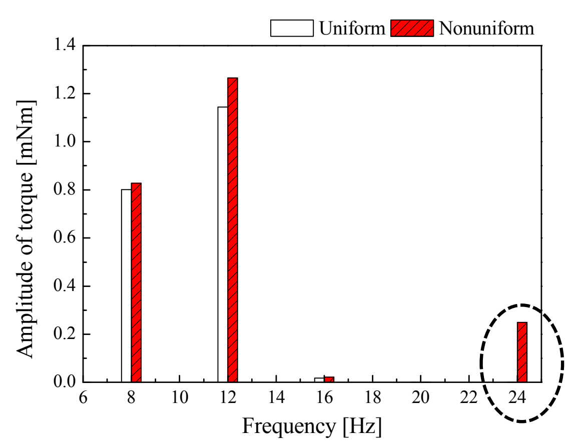

Fig. 3. Harmonic analysis considering axially imperfect remanence

Fig. 3 compares the predicted harmonic analyses of axially uniform and nonuniform magnetization distribution.

It implies that the presence of axially nonuniform magnetization distribution can cause the cogging torque and low order cogging torque components.

B. *Influence of horizontally nonuniform magnetization distribution*

To investigate the effect of horizontally nonuniform magnetization distribution, the remanence of one or two of 8 poles is differently applied.

In the result presented in this analysis, the skewing is not considered.

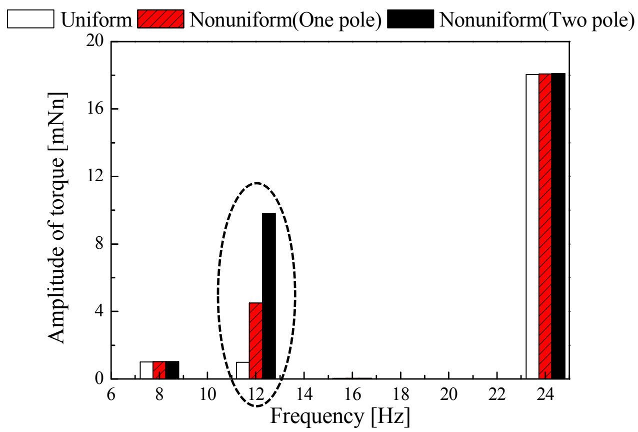

Fig. 4. Harmonic analysis considering horizontally imperfect remanence

Fig. 4 compares the predicted cogging torque of machines having horizontally uniform and nonuniform magnetization distribution, e.g. horizontally nonuniform magnetization distribution means that one or two poles have a remanence of 1.35 T and the rest have a remanence of 1.3 T.

Comparing with the ideal case (the remanence of all magnets is 1.3T), the 12 Hz components are significantly larger.

V. Influence of Eccentricity

Another popular technique used for reducing the cogging torque is to introduce eccentricity. But the defects of the eccentricity can cause an increase in the cogging torque magnitude.

To investigate the effect of eccentricity on the cogging torque, defective eccentricity has been considered. Also, in order to study the influence of defects of eccentricity on IPMSM, the case of SPMSM is compared. Fig. 5 shows the shape of SPMSM and the stator of SPMSM is the same as that of IPMSM. The PM angle / pole pitch is 0.8.

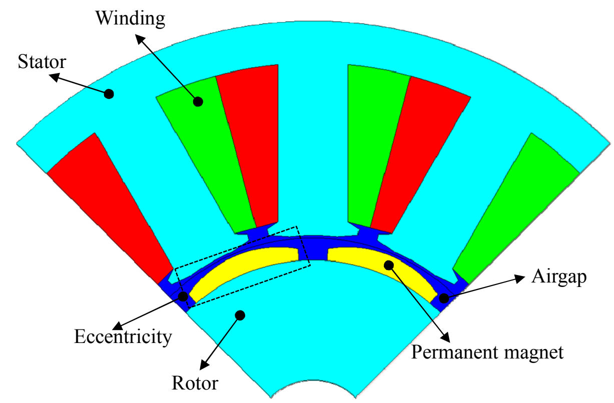

Fig. 5. Configuration of SPMSM

TABLE II
Comparison of Cogging Torque of IPMSM and SPMSM

Eccentricity [mm]	Cogging torque magnitude [mNm]	
	IPMSM	SPMSM
8.0	53.7	72.43
8.5	14.1	83.78
9.0	49.6	92.21
9.5	29.1	96.58
10.0	183.2	94.41

In this analysis, it should be mentioned that the skewing has not been considered. As shown in the TABLE II, the cogging torque of IPMSM is very sensitive to the variations in the eccentricity.

The reason is that for IPMSM, when the airgap length is small, the variations in eccentricity cause the nonuniform airgap and have a significant influence on the cogging torque.

However, for SPMSM, the variations in eccentricity are smaller than the airgap length. Although there are defects of eccentricity in SPMSM, they will cause a negligible change of the airgap length. So it will cause a negligible influence on the cogging torque.

VI. Experimental Results

In order to measure the cogging torque waveform, the test rig, which is shown in Fig. 6 is utilized.

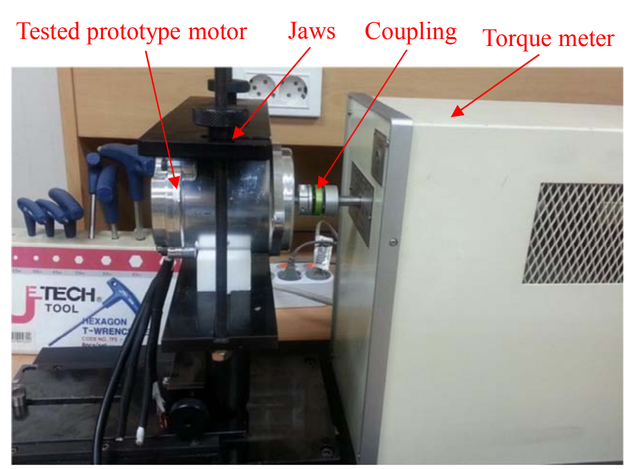

Fig. 6. Experimental machinery for measurement of cogging torque

By rotating the rotor, the torque is measured at different relative positions between the stator and the rotor. The jaws hold the stator of the motor while the rotor is connected to the torque meter.

In this paper, three different prototype motors are used in the experiments and they are all the same except for the skewing.

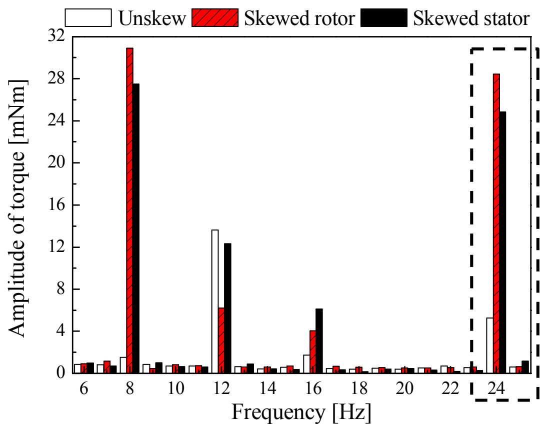

Fig. 7. Harmonic analysis of measured torque

Fig. 7 compares the measured cogging torque and low order components. It shows that the cogging torque of skewed motors is larger than that of an unskewed motor.

It is evident from Fig. 7 that the result of the experiment is quite different from the theories.

Theoretically, the skewing can nearly eliminate the cogging torque. However, the harmonic analysis shown above implies that the presence of defective skewing causes a significant increase in cogging torque magnitude and low order components.

A. *Skewing*

To measure the skew angle, the rotor surface flux density is measured by rotating the step-skewed rotor of Model 1.

The rotor surface flux density is measured at 3 different positions by using a Gauss meter as shown in Fig. 8.

Fig. 8. Measurement of rotor surface flux density

A part of the result is shown below.

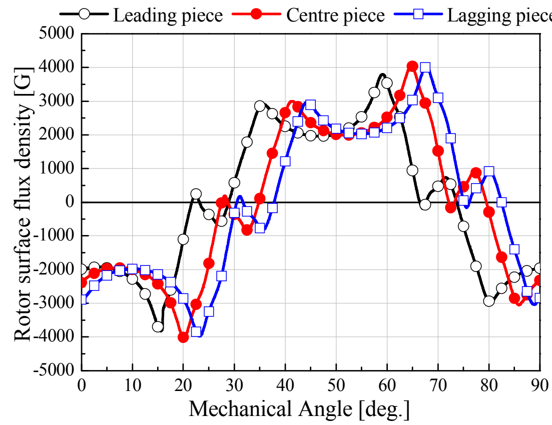

Fig. 9. Rotor surface flux density of a motor having the step-skewed rotor

From Fig. 9, it is found that the skew angle between the leading piece and the centre piece is 5.9 mechanical degrees and that between the centre piece and the lagging piece is 3.0 mechanical degrees. This implies that there are defects of the skew angle and the defective skew angle caused the unexpected cogging torque.

Fig. 10 is an experimental machinery for measurement of the skew angle of slots. To investigate the skew angle of Model 3, a video comparator system is utilized as shown below.

Fig. 10. Measurement of skew angle of slots

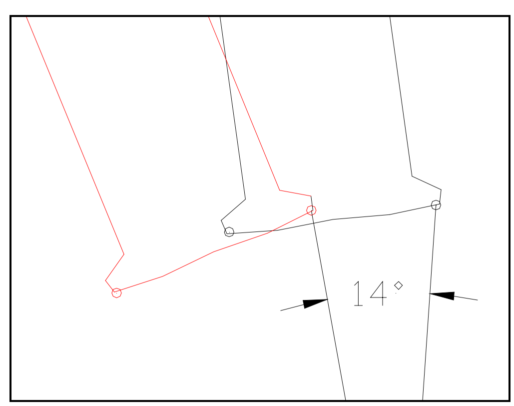

Fig. 11. Measured skew angle of slots

Fig. 11 shows that there exists the defect of the skew angle of Model 3.

From the result of the experiment, it is found that the cogging torque is caused by the defect of skew angle.

B. Magnetization distribution

The rotor surface flux density of all the magnets of Model 2 is illustrated below.

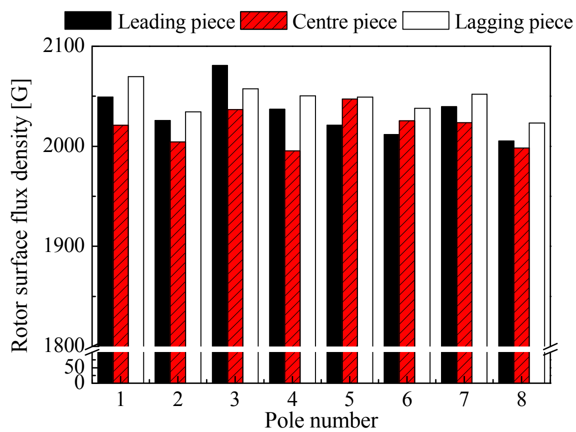

Fig. 12. Rotor surface flux density distribution of Model 2

Fig. 12 shows that the remanence of each magnet is different from every other magnet due to PM imperfection.

It implies that the PM imperfection can cause an increase in the cogging torque magnitude.

C. Eccentricity

The video comparator system is utilized to measure the eccentricity.

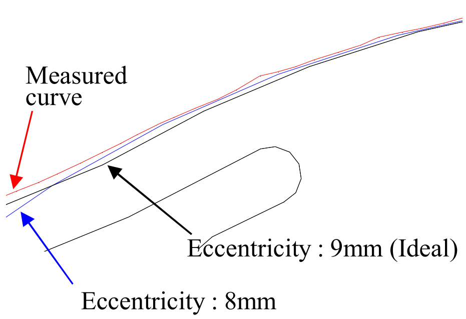

Fig. 13. Comparison of eccentricity

From Fig. 13, it is not easy to measure the eccentricity exactly. However, it is evident that there are manufacturing tolerances of eccentricity and the tolerances influence the cogging torque variations.

VII. CONCLUSION

The influence of tolerances of skew angle, magnetization distribution, eccentricity, which exist due to manufacturing limits, on the cogging torque of PM machines has been analyzed. On the basis of several FE simulations, harmonic analyses and experimental verifications, it is found that manufacturing defects and tolerances can cause the unexpected cogging torque.

Although the cogging torque can be theoretically reduced to zero by the selection of optimum techniques, the cogging torque may not be eliminated due to the unavoidable variations and tolerances.

For example, the skewing technique becomes ineffective when the defective skewing exists. When the nonuniform magnetization distribution exists, the cogging torque and low order components can be generated. Also, the variations in eccentricity of IPMSM strongly influence the cogging torque.

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