Analysis and Design of a New Fault-Tolerant Stator-Permanent-Magnet Motor

Wenxiang Zhao[1, 2], Ming Cheng[1], K.T. Chau[1, 3], Ruiwu Cao[1], and Jinghua Ji[2]
[1]School of Electrical Engineering, Southeast University, Nanjing, China
[2]School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, China
[3]Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong, China
zwx@ujs.edu.cn

Abstract — This paper proposes a new stator-permanent-magnet (PM) motor, namely, the modular flux-switching permanent-magnet (M-FSPM) type, for fault-tolerant (FT) applications. The key is the new motor topology which incorporates the concept of FT teeth to provide the desired decoupling among phases. The proposed FT-FSPM motor not only retains the merits of high power density, strong mechanical integrity, good immunity from thermal problem and high torque capability, but also offers lower torque ripple, higher average torque and lower cost than the conventional one. The power equation, a general design of main parameter and the optimal design considering short-circuit current for the proposed M-FSPM motor are studied. By using finite element method (FEM), the statics characteristics of the proposed FT-FSPM motor is predicted, such as flux linkage, back-EMF, self and mutual inductances and cogging torque. An M-FSPM motor is built for exemplification. The experimental results of the prototype are given to confirm the validity of the proposed motor.

I. INTRODUCTION

Continual operation of motors is extremely important for some applications such as electric vehicles [1],[2]. In recent years, some fault-tolerant (FT) motors, such as the switched reluctance (SR) motor [3] and permanent-magnet (PM) brushless motor [4], have been developed. However, the SR one suffers from relatively low power density while the PM one is mechanically weak in structure [2]. Recently, a new class of brushless motors with PMs located in the stator, so-called the stator-PM motors, has been proposed. These stator-PM motors, including the doubly-salient PM (DSPM) type and flux-switching PM (FSPM) type, can offer high power density, strong mechanical integrity and good immunity from thermal problem. It has been identified that the DSPM motor can inherently offer fault-tolerance [5],[6]. However, its torque capability is significantly lower than that of the FSPM motor [7]. Very recently, by employing an arrangement of alternately wound teeth in the stator, a FT-FSPM motor has also been proposed [8]. Although this FT-FSPM motor can offer high torque capability with fault-tolerance, it suffers from severe asymmetry in flux linkage and hence back-EMF waveforms, thus causing serious torque ripples. Even with the use of rotor skewing to enhance more sinusoidal back-EMF waveforms at the cost of reducing the voltage amplitude, the problem of asymmetry cannot be solved.

The purpose of this paper is to propose a new modular FSPM (M-FSPM) motor, which can not only retain the advantages of the conventional FSPM motor, but also its fault-tolerance. With the use of finite element method (FEM), electromagnetic performance analysis and optimal design of the proposed M-FSPM motors will be performed. Finally, the experimental verification will be given.

II. MACHINE TOPOLOGY

A new 3-phase M-FSPM machine is proposed, which has 24 salient poles in the stator, including 12 armature teeth and 12 FT teeth (FTT), and 14 salient poles in the rotor. Fig. 1 shows the proposed machine. The key is the introduction of FTT between the adjacent stator poles. Thus, the individual windings are essentially isolated among phases, leading to significantly enhance the FT capability. Additionally, those inherent merits of the conventional FSPM machine can be retained, namely high efficiency, high power density, good mechanical integrity, and free from PM thermal problem. Based on the same outside diameters and stack lengths, the proposed M-FSPM motor utilizes 61% less in PMs and 21% more in copper windings than the conventional one so as to produce the same back-EMFs. Since PM material is relatively costly, the proposed motor takes the definite advantage of lower cost.

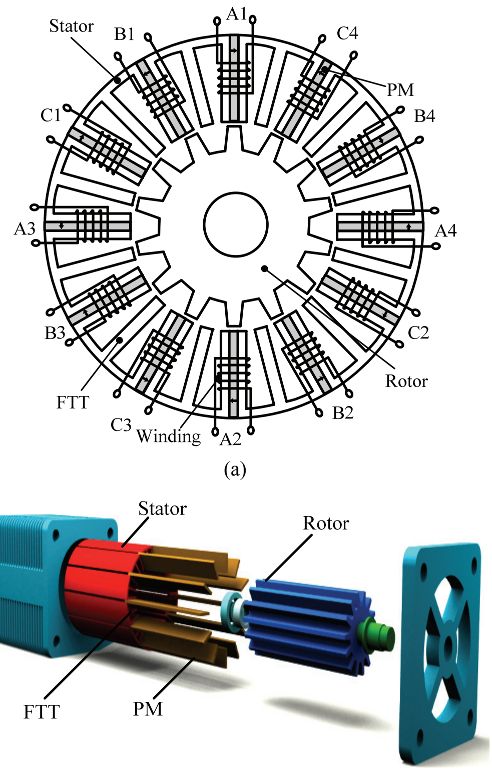

Fig. 1. Topology of M-FSPM motor (a) Cross-section (b) Configuration

III. ELECTROMAGNETIC PERFORMANCE ANALYSIS

Based on FEM, the open-circuit magnetic field distributions of the M-FSPM motor is predicted as shown in Fig. 3. It can be observed that the proposed motor can offer the nature of phase decoupling, namely the magnetic fields of two adjacent phases are independent from one another. Hence, the corresponding self inductances and mutual inductances are calculated. Table I compares its inductances as compared with that of the conventional FSPM motor. It can be found that the ratio of mutual inductance to self inductance of the conventional FSPM motor is much larger than that of the proposed motors, indicating that the conventional one exhibits closely coupled phases while the modular one are essentially phase decoupling.

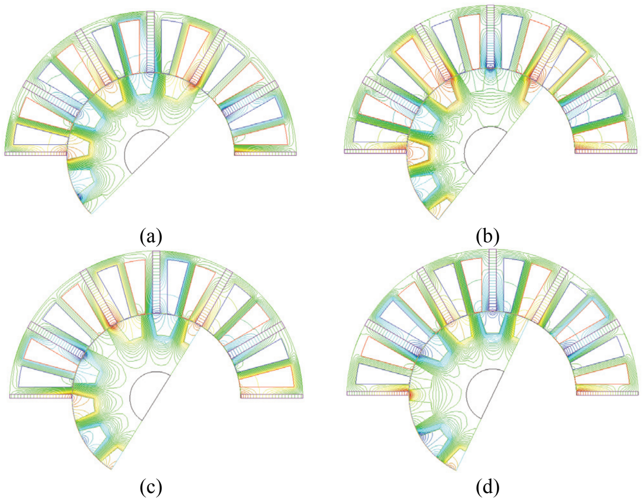

Fig. 2. Open-circuit magnetic field distributions at four typical positions (a) θ_r=0º (b) θ_r=90º (c) θ_r=180º (d) θ_r=270º

TABLE I
COMPARISON OF SELF AND MUTUAL INDUCTANCES

	L (mH)	*M* (mH)	*M*/*L* (%)
Conventional FSPM	1.948	0.930	47.7
Proposed FT-FSPM	4.298	0.550	12.8

IV. OPTIMAL DESIGN

In this section, the power equation, a general design of main parameter and the optimal design for the proposed motor are studied.

V. EXPERIMENTAL VERIFICATION

In order to verify the theoretical analysis, a prototype of M-FSPM motor is designed and built as shown in Fig. 4. The measured winding back-EMF waveform is shown in Fig. 5. As expected, the measured back-EMF waveform closely agrees with the theoretical one.

VI. CONCLUSION

A new three-phase stator-PM motor with modular structure has been proposed, in which the FTT structure is the key to provide the nature of phase decoupling, and hence the property of fault-tolerance. Both the computer simulation and the experimental results confirm the validity of the proposed M-FSPM motor.

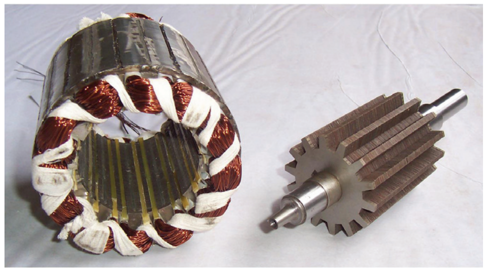

Fig. 4. Prototype motor

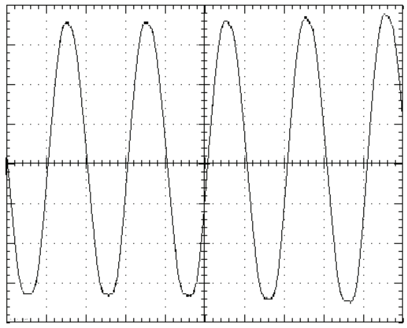

Fig. 5. Measured back-EMF waveform (2 ms/div, 20 V/div)

ACKNOWLEDGMENT

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