Optimal Design of a New Modular Flux-Concentrated Doubly Salient Machine with PMs in Both Stator Yoke and Slot Openings

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This paper proposes a new modular flux-concentrated doubly salient machine(MFCDSM), in which the PMs are employed in both the stator yoke and the slot openings. The magnetic flux excited by the PMs in the stator yoke will be pushed by the PMs in the slot openings to pass through the air-gap and link the rotor, hence its leakage flux is reduced consequently. Meanwhile, the PMs in the stator yoke can act as magnetic reluctance, so the magnetic flux excited by the PMs in the slot openings will also pass through the air-gap and link the rotor, not short-circuited by the salient stator poles. Therefore, the magnetic flux excited by the PMs in both the stator yoke and the slot openings can be concentrated to the air-gap and link the rotor, the torque capability of the proposed machine can be improved. Modular design of the stator can be achieved, which can simplify the manufacturing. Finite element method coupled with an improved Tabu search algorithm, namely FEM-ITS coupled method, is used to optimal design the proposed MFCDSM machine. Its electromagnetic performances are studied in detail using FEM.

***Index Terms*—Doubly salient, flux-concentrated, modular design, optimal design, Tabu search.**

I. Introduction

Doubly salient machines have been extensively researched due to their robust rotor structure, high reliability and easy cooling since most of the heat sources are located on the stator. In order to achieve high torque density, doubly salient permanent magnet machine(DSPMM) has been proposed for many decades [1]. The PMs in the DSPMM can be directly replaced by a dc field winding, which results in a doubly-fed doubly salient machine(DFDSM)[2], and the air-gap flux can be easily adjusted by controlling the dc current.

Both the DSPMM and the DFDSM suffer from nonsinusoidal and asymmetric back-EMF because the flux paths for different phases are not identical, especially when under heavy magnetic saturation, which will result in high torque ripple. Novel variable flux reluctance machines (VFRMs) are developed to solve this problem[3]. The dc field windings are identically located on each pole, and the excitation flux has the same path for each phase. By replacing the dc field windings with PMs in the stator yoke, a new PM machine with baised PM flux linkage and improved torque density can be obtained[4]. Hybrid-excited machines with PMs between adjacent stator poles are also presented to enhence the torque density of doubly salient machines[5]. However, when the dc field current is small, the PM flux will be short-circuited by the stator and no EMF will be induced when the rotor rotates.

In this paper, a new modular flux-concentrated doubly salient machine(MFCDSM) is proposed, in which the PMs are employed on both the stator yoke and the slot openings. High torque density can be achieved because the PM flux can be concentrated to pass through the air-gap and link the rotor, so the leakage flux can be well reduced. With the merits of modular stator design, the manufacturing cost of the proposed machine can be reduced. Finite element method coupled with an improved Tabu search algorithm[6], which is referred as FEM-ITS coupled method, is used to optimal design the proposed machine. The electromagnetic performances are investigated in detail using FEM.

II. Machine Configuration

Fig. 1 shows the configuration of the proposed MFCDSM and its stator module. The stator consists of T-shaped modular segments, between which are mounted with PMs. The armature windings are concentric wound on the stator teeth. Each stator module consists of one stator tooth and one tooth-wound coil, the total number of stator modules is equal to the number of stator teeth. PMs are employed on both the stator yoke and the slot openings, the adjacent PMs are magnetized in opposite direction, therefore the PM flux can be concentrated to the air-gap and link the rotor. The rotor is simply made up of salient poles, which is mechanically robust. Various combinations of the stator slot number and rotor pole number can be used in the MFCDSM. In the proposed design in this paper, the stator slot number and rotor pole number is 12 and 11, respectively. The stator and rotor pole numbers are differed by one, which can result in sinusoidal back electromagnetic force(EMF) and reduce the torque ripple[4].

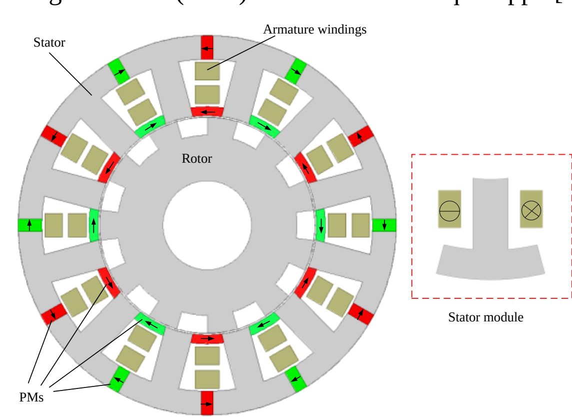

Fig. 1. Configuration of the proposed MFCDSM and its stator module.

III. Optimal Design and Performance Analysis

Before investigating the electromagnetic performances, the proposed MFCDSM is optimal designed using FEM-ITS coupled method. Three objectives are investigated, which include the average output torque f_1, the torque ripple ratio f_2 and the efficiency f_3. The optimal design problem is formulated as

$$\min\{-f_1(x), f_2(x), -f_3(x)\}, \qquad x \in F \tag{1}$$

where x refers to the design parameters and F refers to the constraints of the design parameters. Fig. 2 shows the optimization results of the efficiency and the average output torque, it can be observed that the efficiency is positive correlated with the average output torque. The relationship between the torque ripple ratio and the average output torque is given in Fig. 3. After the multi-objective optimization, the proposed machine is optimized through single objective optimization. The objective is to achieve the optimal output torque and the constraint is the torque ripple ratio should lower than 12%. The average output torque versus iterative number is shown in Fig. 4, one can see that the optimization can convergent within 20 iterations, which shows the effectiveness of the optimization method.

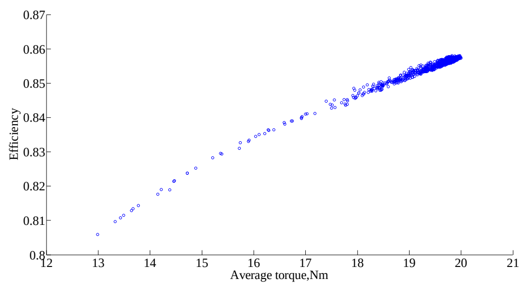

Fig. 2. The relationship between efficiency and average torque.

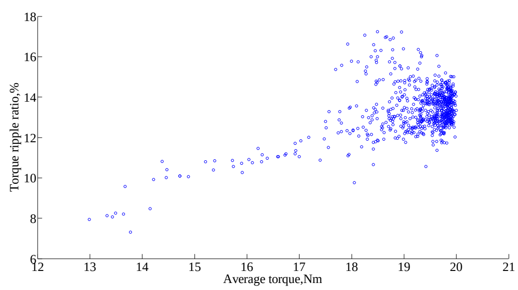

Fig. 3. The relationship between torque ripple ratio and average torque.

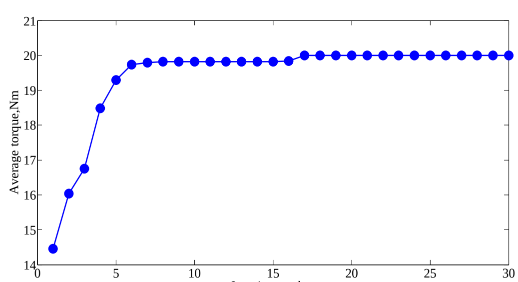

Fig. 4. The average torque at different iterative number.

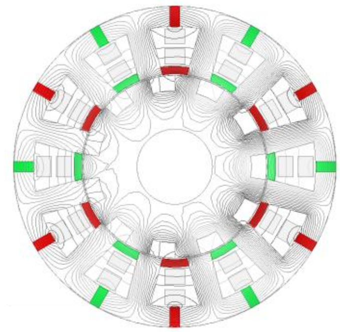

Fig. 5. No load flux line distribution.

Fig. 5 shows the no load flux line distribution of the MFCDSM, it can be observed that the PM flux can be well concentrated to the air-gap and link the rotor. The no load back EMF waveforms when the proposed machine runs at 273rpm are shown in Fig. 6. Fig. 7 shows the output torque when different RMS currents are applied. It can be observed that the output torque increases with the increasing of RMS current, the largest torque reaches 25.7Nm when 50A RMS current is applied. When the RMS current is larger than 35A, the torque-current curve becomes flat due to magnetic saturation.

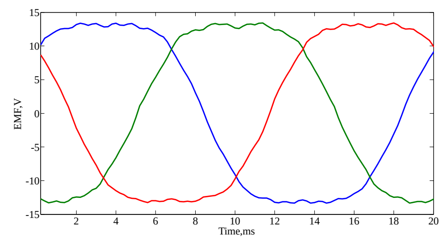

Fig. 6. No load back EMF waveforms.

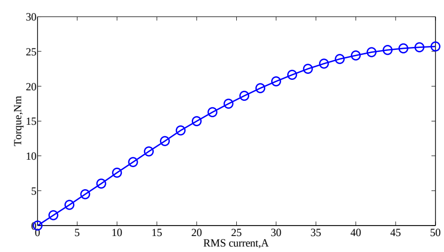

Fig. 7. Output torque when applied with different RMS currents.

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