Investigation of Optimal Split Ratio in Brushless Dual-Rotor Flux-Switching Permanent Magnet Machine Considering Power Allocation

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This paper investigates an optimal split ratio for a brushless dual-rotor flux-switching permanent magnet (BDR-FSPM) machine. Based on the basic design principle of the FSPM machine, the split ratio of the BDR-FSPM machine is deduced and redefined, which is purposely divided into two parts for reasonable optimization, consisting of outer split ratio for outer motor and inner split ratio for inner motor. The magnetic coupling and magnetic loading are chosen to be the study objectives, which contributes to guaranteeing an independent and desirable power/torque output for the inner and outer motors of BDR-FSPM machine. Additionally, considering the hybrid electric vehicles (HEVs) application, the concept of power allocation is proposed and integrated into the investigation process of split ratio. Then based on the finite element (FE) method, the motor performances are analyzed in details, including airgap flux density, back-EMF, coupling-EMF, power characteristic. Finally, a 5kW prototype machine is manufactured to verify the validity.

***Index Terms*—Dual-rotor flux-switching permanent magnet machine, optimization design, split ratio, power allocation.**

I. Introduction

DUAL-ROTOR permanent magnet (DR-PM) machines have attracted increasing concern in recent years, which mainly because they can provide the higher torque density and more abundant driving modes than conventional single-rotor PM machines [1]. In existing studies, many machine topologies have been proposed and realized, which can be classified into two types generally, including single-output DR-PM machines and dual-output DR-PM machines [2], [3].

In [2], on the one hand, a type of single-output DR-PM machine is proposed for hybrid electric vehicles (HEVs), where the two rotors are connected together by one end disk, forming the whole rotating rotor. In such motor, the airgap magnetic fields of inside and outside can be superposed together to boost the torque capability. On the other hand, in [3], a type of dual-output DR-PM machine is proposed, in which two rotors and two sets of windings are integrated into one machine frame. The study reveals that the motor can not only offer a multiple operation modes, but also realize a high integration. Hence, it is more preferred by the researchers on HEVs driving motors. Yet, regardless of the single-output DR-PM machine or dual-output one, their design essences are all the high integration of two separated machines into one motor frame. And then the power and torque of the DR-PM machine will be directly determined by its inner and outer motors. Thus, reasonable power allocation and design is necessary for the type of DR-PM machines.

Recently, split ratio has been considered as one of the most crucial design variables mainly due to its significant effects on machine performances, such as the power output and torque capability [4]. Previous study [5] explores an optimal split ratio for an interior permanent magnet synchronous machine (PMSM), and it is defined as stator radius/rotor radius. And the results indicate that the optimal split ratio results in the improvement of power and torque. Then the purpose of this paper is to investigate an optimal split ratio for a brushless dual-rotor flux-switching permanent magnet (BDR-FSPM) machine, which contributes to obtaining a reasonable power allocation for the inner and outer motors. In the process of investigation, the magnetic loading, magnetic coupling, and power split ratio are all considered for the optimal split ratio. The theoretical analysis is exanimated by finite element (FE) method and validated by experimental results.

II. Machine Structure

Fig. 1 shows the BDR-FSPM machine and its parameter definitions. It can be seen from the Fig. 1 (a) that the motor has three parts, consisting of two rotating rotors and one stator, in which the two rotors are respectively arranged in the inside and outside of the motor and the stator is sandwiched between them, as shown in Fig. 1 (b). And since the two rotors are independent, various power and torque can be transferred by these two mechanical ports. Then to design conveniently, the corresponding design parameters are also defined in Fig. 1 (b).

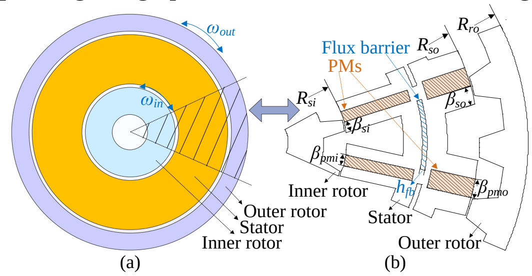

Fig. 1. Motor structure and parameter definition. (a) Motor structure. (b) Parameter definition.

III. Split Ratio Optimization

Based on the power equation of flux switching machine, the split ratio of BDR-FSPM machine can be deduced as

$$k_{tr}=\frac{R_{so}\big/(R_{ro}-12\mathrm{mm})}{R_{si}\big/(R_{ro}-12mm)}=\frac{k_{out}}{k_{in}}=\frac{P_{om}}{P_{im}}\times\frac{B_{gmaxi}\beta_{si}}{B_{gmaxo}\beta_{so}} \qquad (1)$$

where k_{out} and k_{in} represent the outer and inner split ratios, β_{so} and β_{si} are the stator pole arc widths of outer and inner motors. And based on (1), power split ratio k_{ps} of BDR-FSPM machine can be defined as the relationship of $k_{PA}=P_{om}/P_{im}$. Apart from k_{ps}, β_{so} and β_{si} in (1), the magnetic loadings of B_{gmaxo} and B_{gmaxi} are related to the k_{tr}. And the B_{gmaxo} and B_{gmaxi} are determined by the PM pole arc widths of β_{pmo} and β_{pmi}. Hence, the β_{so}, β_{si}, β_{pmo} and β_{pmi} are selected for exploring an optimal split ratio.

A. Influence of Split Ratio on Magnetic Loading

Fig. 2 shows the influence of the split ratios and the design parameters on magnetic loading. Considering the relatively high magnetic saturation in the type of flux-switching machine, the magnetic loadings of B_{gmaxo} and B_{gmaxi} are preferable to be designed with 1.7T and 1.5T respectively. Consequently, from Fig. 2 (a) to (d), the β_{so}, β_{si}, β_{pmo} and β_{pmi} can be respectively determined with the value of 4.2deg, 7deg, 2.6deg, and 3.3deg. According to the values of the magnetic loadings and design parameters, the k_{out} is suitable choosing from 0.85 to 0.94, while the value range of k_{in} is from 0.321 to 0.426.

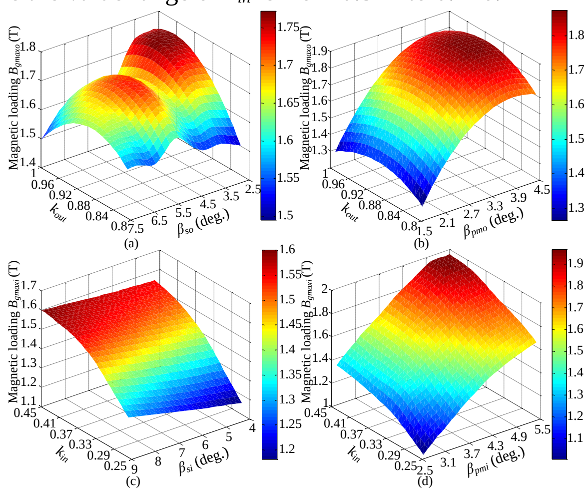

Fig. 2. Variation relationships among magnetic loadings, design parameters, and split ratios. (a) β_{so}, k_{out} and B_{gmaxo}. (b) β_{pmo}, k_{out} and B_{gmaxo}. (c) β_{si}, k_{in} and B_{gmaxi}. (d) β_{pmi}, k_{in} and B_{gmaxi}.

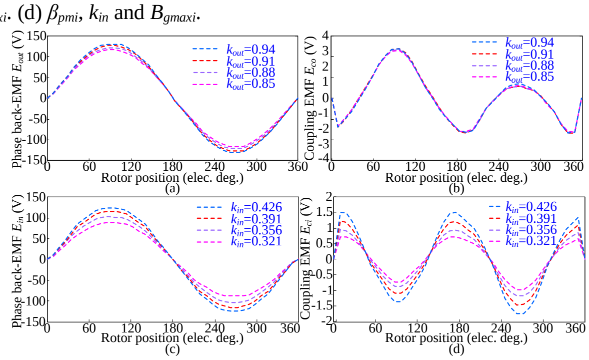

Fig. 3. Magnetic coupling analysis. (a) Outer back-EMF E_{out}. (b) Coupling EMF E_{co}. (c) Inner back-EMF E_{in}. (d) Coupling EMF E_{ci}.

B. Influence of Split Ratio on Magnetic Coupling

The effects of split ratios on back-EMF and coupling-EMF are depicted in Fig. 3. From the Fig. 3 (a) and (b), with the raise of k_{out}, the ratio of coupling-EMF E_{co} on back-EMF E_{out} is decline. In contrast, the increase of k_{in} leads to the increase of the ratio of coupling-EMF E_{ci} on back-EMF E_{in}, as shown in the Fig. 3 (c) and (d). It indicates that the low magnetic coupling can be obtained in a large k_{out} and small k_{in}. Besides, it can be seen from Fig. 3 (a) and (c) that when the k_{out}=0.91 and k_{in}=0.356, the outer and inner back-EMF have sinusoidal and symmetrical waveforms than other conditions. And the E_{co} accounts for 2.5% value of the E_{out}, while the percentage of the E_{ci} on the E_{in} is also low, only accounting for 1.8%, indicating a low magnetic coupling.

C. Influence of Split Ratio on Power Allocation

In this paper, the power specification of the BDR-FSPM machine is 5kW, and the power split ratio between the outer and inner motors is preferred to be designed in the range from 3 to 3.5 based on the specific requirements of HEVs. Then Fig. 4 shows that the power performances with respect to split ratios. Based on the requirements mentioned above, from the Fig. 4 (a) to (d), the optimal split ratios of k_{tr}, k_{out} and k_{in} can be respectively determined as 2.56, 0.91 and 0.356 with a tradeoff consideration, thus the power split ratio k_{PA} and total power can finally reach the values of 3.17 and 5kW.

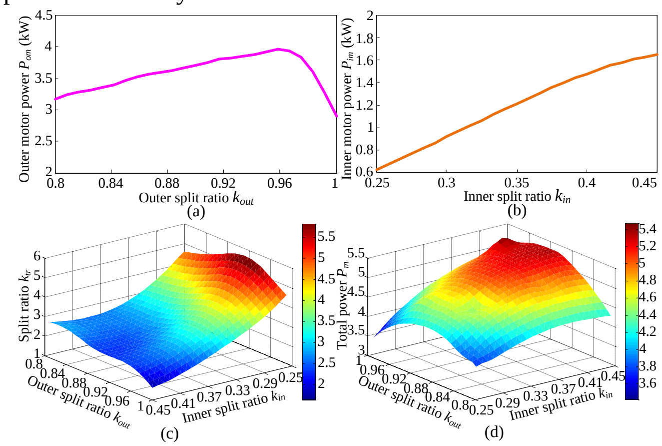

Fig. 4. Power characteristics. (a) P_{om} and k_{out}. (b) P_{im} and k_{in}. (c) k_{tr}, k_{out}, and k_{in}. (d) P_m, k_{out} , and k_{in}

D. Experimental Validation

To further verify the optimal split ratio of k_{tr}=2.56, a 5kW prototype machine is manufactured and tested, as depicted in Fig. 5. And the Fig. 5 (a) shows the silicon steel sheet. The measured back-EMF E_{out} and its coupling-EMF E_{co} are given in Fig. 5 (b), which is agreed with the results in Fig. 3 (a) and (b), thus verifying the validation of optimal split ratio. More detailed performances analysis and experimental results will be presented in the full paper to verify the validity.

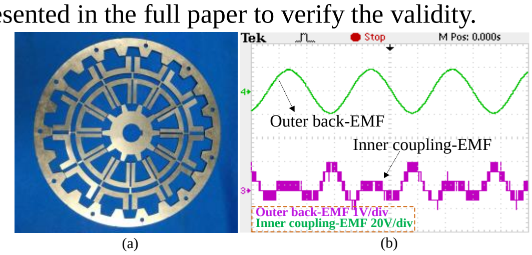

Fig. 5. Experimental validation. (a) Silicon steel sheet. (b) Measured back-EMF of outer motor and its coupling-EMF.

REFERENCES

[1] I. Boldea, L. N. Tutelea, L. Parsa, and D. Dorrell, "Automotive electric propulsion system with reduced or no permanent magnets: an overview," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5696-5711, Oct. 2014.

[2] R. Qu, and T. A. Lipo, "Dual-rotor, radial-flux, toroidally wound permanent-magnet machines," *IEEE Trans. Ind. Appl.*, vol. 45, no. 6, pp. 1665-1673, Nov./Dec. 2003.

[3] Y. Yeh, M. Hsieh, D. G. Dorrell, "Different arrangements for dual-rotor dual-output radial-flux motors," *IEEE Trans. Ind. Appl.*, vol. 48, no. 2, pp. 612-622, Mar./Apr. 2012.

[4] R. Cao, C. Mi, and M. Cheng, "Quantitative comparison of flux-switching permanent-magnet motors with interior permanent magnet motor for EV, HEV, AND PHEV applications," *IEEE Trans. Magn.*, vol. 48, no. 8, pp. 2374-2384, Aug. 2012.

[5] Y. shen and Z. Q. Zhu, "Analytical prediction of optimal split ratio for fractional-slot external rotor PM brushless machines," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 4187-4190, Oct. 2011.