Optimization Design and Analysis of a Hybrid Permanent Magnet Flux-Switching Motor with Compound Rotor Configuration

Zixuan Xiang, Xiaoyong Zhu, Li Quan, and Deyang Fan

***Abstract*—This paper proposes a type of flux-switching permanent magnet (FSPM) motor, where the design concept of the hybrid permanent magnets (HPM) and the compound rotor are incorporated into the motor design. In such design, the proposed motor can not only realize the significant reduction of NdFeB volume, but also artfully convert external magnetic flux leakage into the air-gap field to achieve competitive torque density and desirable PM usage efficiency. For extensive investigation, two topologies of the HPM are designed and analyzed for the proposed motor, which consist of the parallel-magnetic-hybrid (PMH) mode and serial-magnetic-hybrid (SMH) mode. To fully exploit the potential advantages of the proposed motor, a multi-objective optimization design is conducted, where the response surface method (RSM) and sequential non-linear programming (SNP) method are purposely utilized. After optimization, the electromagnetic performances of the motor with PMH mode and SMH mode are evaluated and compared by using finite element method (FEM), which include the back-EMF, cogging torque, output torque, and so on. Furthermore, the partial demagnetization of the ferrite PM is also investigated in the paper. Finally, the theoretical analysis and simulation study verify the effectiveness of the proposed motor and corresponding optimization design.**

***Index Terms*—Electromagnetic performances, flux-switching permanent magnet (FSPM) motor, hybrid permanent magnets (HPM), multi-objective optimization.**

I. INTRODUCTION

RARE-EARTH permanent magnet flux-switching (RE-PMFS) motors have aroused considerable attention in recent decade because of its several key merits of high torque density high efficiency and simple and robust rotor structure [1], [2]. So it has been considered as one of the potential alternative motor schemes for many applications, such as aerospace application, wind power generation system and electric vehicle [3]-[5]. It is worth noting that, to the type of RE-PMFS motors, a large amount of rare-earth permanent magnet (REPM) materials is usually required to be utilized in motor stator, which will greatly result in a high manufacturing cost [6]-[8]. In addition, the motors have the inevitable PM leakage flux in stator, which will leads to a relatively low PM utilization [9]. Especially, in recent years, with the REPM materials are beginning to be established as the strategic resources reserve, the problems of the price increase and unstable resource supplies are arises gradually [10]. And then, the limitations of the RE-PMFS motors are emerging with the high cost and limited supply of REPM materials, which impede their potential developments and applications to large extent.

To address these problems, many motor designers are paid their efforts to explore and investigate the effective solutions for reducing the REPM usage [11]. It makes the less-REPM flux-switching motor or non-REPM one is becoming a hot study orientation in motor field. To reduce the consumption of the REPM, some effective design schemes are investigated in [12]-[14]. In [12], an optimization design is conducted for the RE-PMFS motor, where the stator inner radius of the motor is enlarged purposely for effectively reducing the REPM volume. The results confirm that, in such design, the consumption of the REPM can is reduced obviously, while the output torque is also decreasing. Facing such problems, a type of hybrid-excited PMFS motors is proposed and investigated, in which the less REPM and DC winding are utilized together as the excitation source [13]. The study reveals that the features of the relatively high torque and variable airgap magnetic field are obtained in such motor design. Yet, the extra excitation loss is inevitable due to the adoption of DC winding, which will lead to the deteriorated operation efficiency to some extent. To solve these problems, a type of double stator PMFS motor with ferrite PM is proposed in [14], which possesses the features of the low-cost and multiple operation modes. Yet, the flux leakage problems are still existed in the motor, indicating that the motor has the relatively low PM utilization and torque density to some extent. Thus, to the less-REPM flux-switching motor or non-REPM one, how to realize the desired cost-effectiveness and maintain a high torque density with reduced REPM is full of challenge.

In addition, to the less or no REPM flux-switching motor, the existing studies mainly concentrate on the topology design and performance comparison, while the optimization analysis is

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seldom involved. It is noted that, in the driving process, there are more than one motor performance in need of consideration, such as the output torque, torque ripple, efficiency, and so on [15]. It means that the motor optimization design actually belongs to multidimensional calculation problem, which has relatively large amount of calculation and is always required to be conducted efficiently by using some effective optimization methods [16]. And many studies verify that the tradeoff designs and comprehensive considerations between various motor performances can be achieved effectively by utilizing appropriated optimization methods, such as the system-level optimization method, multi-level optimization method, and multidisciplinary design optimization method [17]-[21]. Thus, to realize the high performances on less-REPM or non-REPM flux-switching motor, the multi-objective optimization study is important and meaningful.

The main purpose of this paper is to propose a type of hybrid permanent magnet (HPM) flux-switching motor with compound rotor configuration, which can effectively solve the problem of external flux leakage and is termed as C-HPMFS motor. To the H-PM, it includes the high-magnetic-energy NdFeB and the low-cost non-rare-earth ferrite PM, which contributes to simultaneously realizing high torque density and reduced REPM consumption. To analyze extensively, two types of H-PM topologies are proposed and presented in section II, including parallel-magnetic-hybrid (PMH) mode and serial-magnetic-hybrid (SMH) mode. And in the section, the operation principle of the proposed motor with the two modes is also analyzed. To obtain the optimal motor performances, a multi-objective optimization is conducted in section III. After optimization, no-load characteristics and torque performances of the proposed motor are predicted in section IV. Furthermore, the demagnetization characteristics of the motor with the PMH mode and SMH mode are also investigated in this section, which is mainly due to the different magnetic energy between the excitation sources of NdFeB and ferrite. Finally, conclusion is drawn in section V.

II. Motor Configuration and Operation Principle

A. Motor Configuration

Fig. 1 (a) shows the proposed C-HPMFS motor with a 6-pole rotor/7-slot stator/6-pole rotor configuration, where the concentrated winding and HPM topology are utilized in motor design. It can be seen that the two rotor parts are connected together as one component by an end disc, which forms the so-called compound rotor. It can be a cooling fan in motor drive to improve the capability of heat dissipation. From Fig. 1 (b), the compound rotor is assembled with the I-shaped modular stator, which forms the unique structure of double air-gaps. It artfully avoids the problem of the PM flux leakage in stator, which contributes to improving the PM utilizations. Moreover, to the HPM, two various topologies of the PMH mode and SMH mode are presented in the section, as depicted in Fig.2. It can be seen from Fig. 2 (a) that the ferrite PM of PMH mode is sandwiched between the two parts of NdFeB in radial direction, thus indicating that the corresponding magnetic field of the two PMs will be in parallel. Meanwhile, to the SMH mode, the ferrite of HPM is sandwiched between the two parts of NdFeB in tangential direction. Obviously, from Fig. 2 (b), the magnetic field between the two PMs in such mode will be in series.

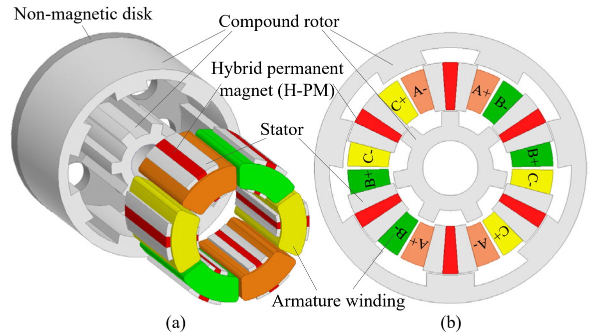

Fig. 1. Cross section of the C-H-PMFS motor.

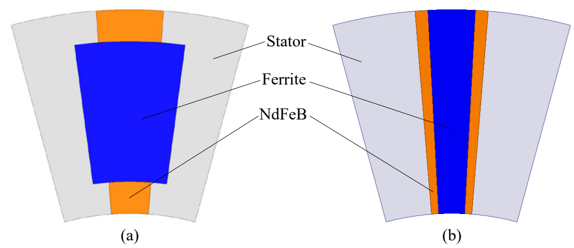

Fig. 2. Two topologies of the HPM. (a) PMH mode. (b) SMH mode.

B. Operation Principle

Fig. 3 shows the operation principle of the C-HPMFS motor with the PMH mode and SMH mode. Due to the no-stator-yoke design of the proposed motor, the flux path is different from that in the conventional PM motors. It can be seen from Fig. 3 that regardless of the proposed motor in SMH mode or PMH mode, a significant series magnetic circuit is built between the inner and outer air-gaps. Thus, in this special design, the leakage flux can be artfully converted into the high usage efficiency of the PM materials, indicating that the improved PM utilization can be realized. And it further infers that the torque density of the motor can also be increased. Furthermore, at position of the positive maximum flux, the flux path passes through the concentrated coil which is wound around the stator pole in a counterclockwise direction, while the flux path goes across the coil in a clockwise direction at position of the negative maximum flux. Therefore, a bipolar back-EMF can be induced when the rotor position is continually switched.

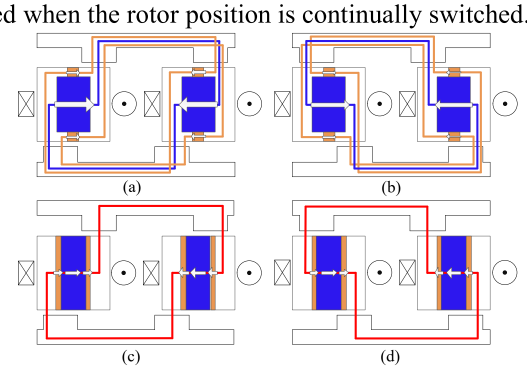

Fig. 3. Operation principle of the proposed motor. (a) The maximum flux in SMH mode at negative position. (b) The maximum flux in SMH mode at positive position. (c) The maximum flux in PMH mode at negative position. (d) The motor in PMH mode at positive position.

III. Multi-Objective Optimization Design for The C-HPMFS Motor

A. *Optimization objectives and Leading Parameters*

Considering the special requirements in drive applications, the torque ripple of the motor usually needs to be limited below an acceptable level, while its torque capability requires to be maintained at a desirable degree. And then, the output torque and torque ripple are always considered to be the important motor performances in motor optimization design. So the output torque and torque ripple of the C-HPMFS motor are selected purposely as the design objectives in this section.

Furthermore, to the type of FSPM motors, the stator tooth width, rotor tooth width and PM width are the leading parameters, which possess significant influence on the torque and torque ripple of motor [12]. So based on the design experience of the conventional FSPM motor, some leading parameters are selected and defined in Fig. 4.

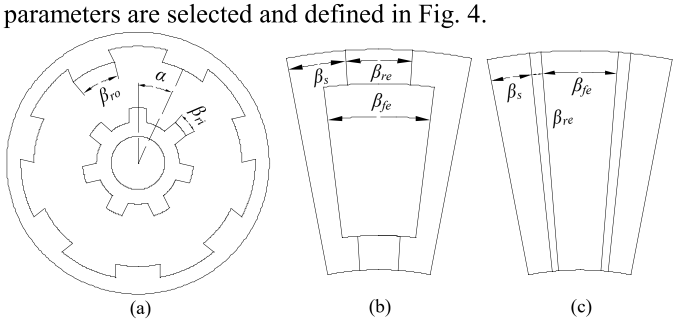

Fig. 4. Design parameters. (a) Compound rotor. (b) PMH-stator. (c) SMH-stator.

The relative position angle α between inner rotor and outer rotor can be given by

$$\alpha = \frac{\pi}{N_r} \tag{1}$$

where N_r is the rotor pole number. Given all the features of the double air-gaps, the stator core and H-PM are designed as a sector structure. Besides, the leading parameters include the stator tooth width β_s, outer rotor tooth width β_{ro}, inner rotor tooth width β_{ri}, ferrite width β_{fe}, NdFeB width β_{re}. For convenient analysis, the corresponding computing coefficients are defined as

$$k_s = \beta_s / c_s \tag{2}$$

$$k_{ro} = \beta_{ro} / c_r \,, k_{ri} = \beta_{ri} / c_r \tag{3}$$

$$k_{fe} = \beta_{fe} / c_s \,, k_{re} = \beta_{re} / c_s \tag{4}$$

where c_r and c_s are the rotor pole arc coefficient and stator pole arc coefficient, respectively. k_s is stator tooth width coefficient, k_{ro} is outer rotor tooth width coefficient, k_{ri} is inner rotor tooth width coefficient, k_{fe} is ferrite width coefficient, k_{re} is NdFeB width coefficient.

B. *Response Surface analysis and Optimization*

To clearly and quickly obtain the variation regularity and calculate data between the objective performances and design variables, the response surface method (RSM) is adopted in this part. And based on the theory of the RSM [16], the response model of the C-HPMFS motor can be written as

$$f = \beta_0 + \sum_{i=1}^{k} \beta_i z_i + \sum_{i=1}^{k} \beta_{ii} z_i^2 + \sum_{i=1, i<j}^{k} \beta_{ij} z_i z_j + \sigma \tag{5}$$

where f is the predicted value of the torque or torque ripple, k is the number of design variables. Besides, β represents the regression coefficient, z denotes the design variable, and σ is the error. In this paper, k is equal to 5. According to (6), the response surface results of C-HPMFS motor with PMH mode and SMH mode can be calculated. And the specific calculated results are presented in Fig. 5 and Fig. 6.

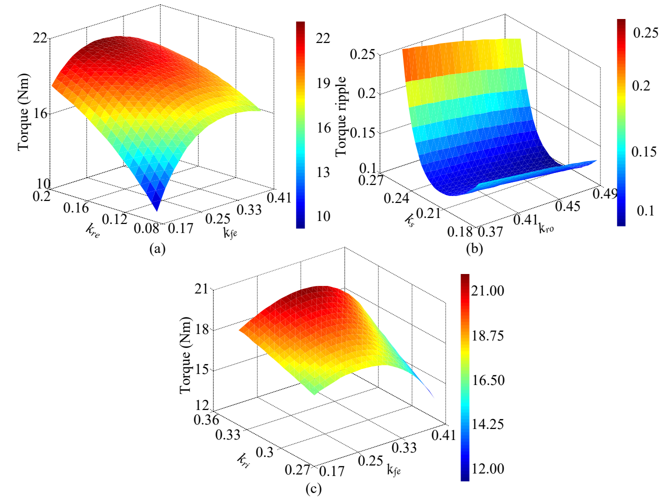

Fig. 5. The response surface analysis results of the proposed C-HPMFS motor with PMH mode. (a) Torque varies with k_{fe} and k_{re}. (b) Torque ripple varies with k_s and k_{ro}. (c) Torque varies with k_{fe} and k_{ri}.

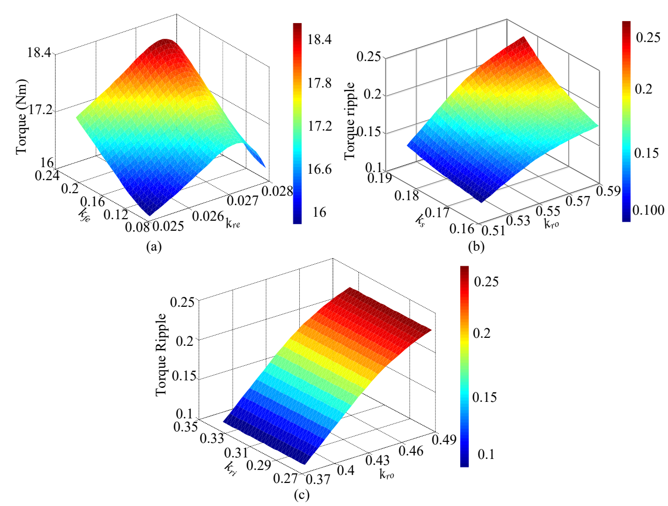

Fig. 6. The response surface analysis results of the proposed C-HPMFS motor with SMH mode. (a) Torque varies with k_{fe} and k_{re}. (b) Torque ripple varies with k_s and k_{ro}. (c) Torque varies with k_{fe} and k_{ri}.

From these figures, there are some conflicts among the choice of these leading parameters, and thus a reasonable tradeoff among output torque and torque ripple needs to be considered carefully. To realize the relatively high average output torque and comparatively low torque ripple for the torque performance, the sequential non-linear programming (SNP) optimization method is utilized for conducting the following multi-objective optimization. The corresponding optimization function $f_{min}(z_i)$ can be given as

$$f_{\min}(z_i)=\frac{T_{outi}}{T_{out}(z_i)}+\frac{T_{ri}(z_i)}{T_{rii}} \tag{6}$$

where T_{outi} and T_{rii} are the initial values of the output torque and torque ripple, while $T_{out}(z_i)$ and $T_{ri}(z_i)$ are the corresponding optimal values. z_i is the design variables. Based on (6), the optimize solutions are presented in Fig. 7. It can be seen that, based on comprehensive consideration, the PMH mode can offer the output torque of 20.2Nm and torque ripple of 0.118, while the SMH mode can provide the objective performances of 17.5Nm and 0.097. And the optimal values of the design parameters and objective performances are listed in Table I.

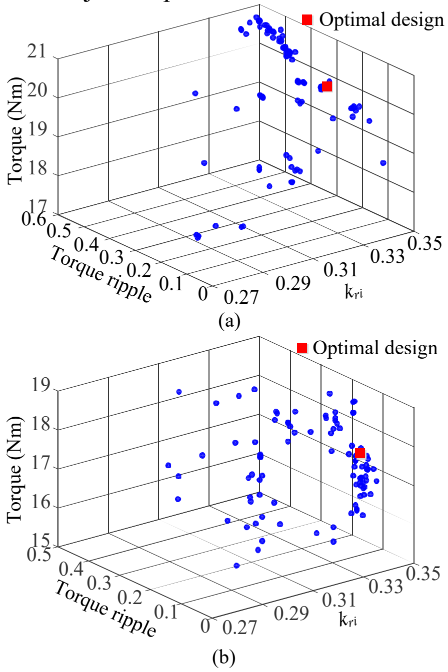

Fig. 7. Selection of optimal design scheme. (a) PMH mode. (b) SMH mode.

TABLE I
KEY DESIGN PARAMETERS AND OBJECTIVE PERFORMANCES

Items	PMH mode	SMH mode
Outer rotor tooth width β_{ro}	21deg	28deg
Inner rotor tooth width β_{ri}	16deg	20deg
Stator tooth width β_s	13.5deg	10.5deg
FPM width β_{fe}	17deg	6deg
NdFeB width β_{re}	8deg	1.6
Output torque	20.2Nm	17.5Nm
Torque ripple	0.118	0.097

IV. ELECTROMAGNETIC PERFORMANCE ANALYSIS

A. No-load Characteristic

Fig. 8 shows the C-HPMFS motor with PMH mode and SMH mode. It can be observed that the flux between the NdFeB and ferrite is parallel in the PMH mode, while it is serial in the SMH mode. Whether in PMH mode or in the SMH mode, an obvious serial flux path between the outer air-gap and the inner air-gap is formed by the compound rotor. In Fig.9 (a) and (b), the no-load air-gap flux densities of both PMH mode and SMH mode are calculated for the proposed motor. And two situations are investigated respectively for the two modes, which include the NdFeB and the ferrite work together and the NdFeB works alone. It can be indicated that the ferrite are mainly functioned as an assistant excitation both in the PMH mode and SMH mode. In addition, the no-load back-EMF waveforms per turn of the proposed motor both in PMH mode and SMH mode are shown in Fig. 9 (c). It can be seen that the proposed motor can provide sinusoidal and symmetrical three-phase no-load back-EMF waveforms, which conforms that it is suitable for BLAC operation.

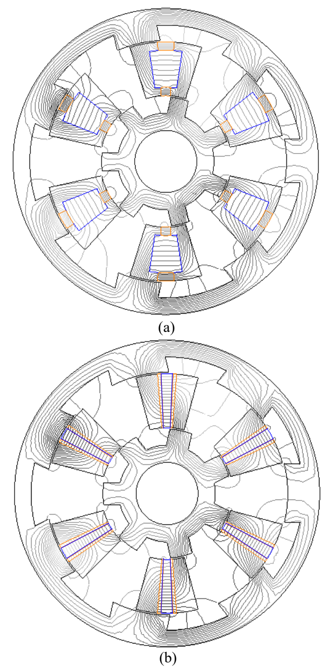

Fig. 8. Flux distributions. (a) PMH mode. (b) SMH mode.

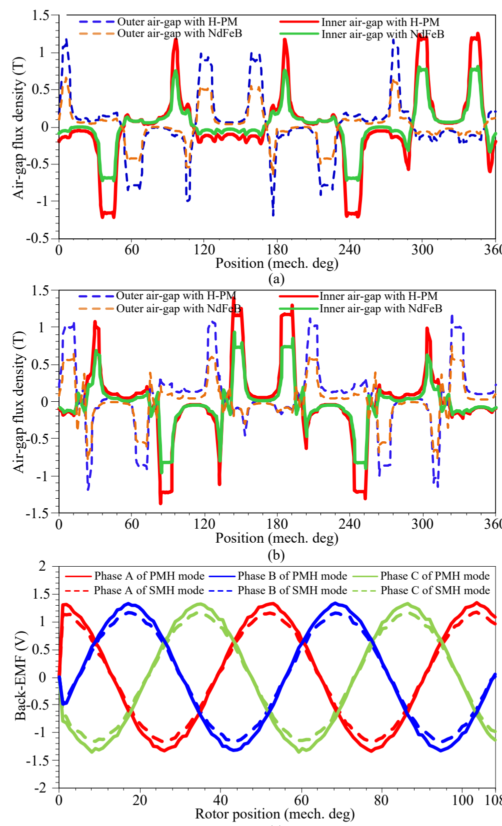

Fig. 9. No-load air-gap flux densities and back-EMF waveforms. (a) Air-gap flux densities in PMH mode. (b) Air-gap flux densities in SMH mode. (c) Back-EMF waveforms.

B. Torque Performances

The overall cogging torque of the proposed motor consists of the inner portion which is produced in the inner air-gap and the outer portion that is produced in the outer air-gap. Fig. 10 (a) and (b) demonstrate the cogging torque waveforms. It can be observed that the motor in PMH mode offers a lower cogging torque than that in SMG mode obviously. It is worth noting that the overall cogging torque is weakened in PMH mode when the waveforms of the inner portion and outer portion are phase shifted, while it is strengthened in SMH mode when the waveforms are exactly in phase. Moreover, Fig. 10 (c) indicates the average output torque and its corresponding torque ripple with various armatures current. It can be seen that the motor in SMH mode provides a better overload characteristic than that in PMH mode, while the latter offers the better torque capability than the former. Besides, the two motors can provides the acceptable torque ripple which no more than 12% on the overload current, which agree with the optimization result in Table I.

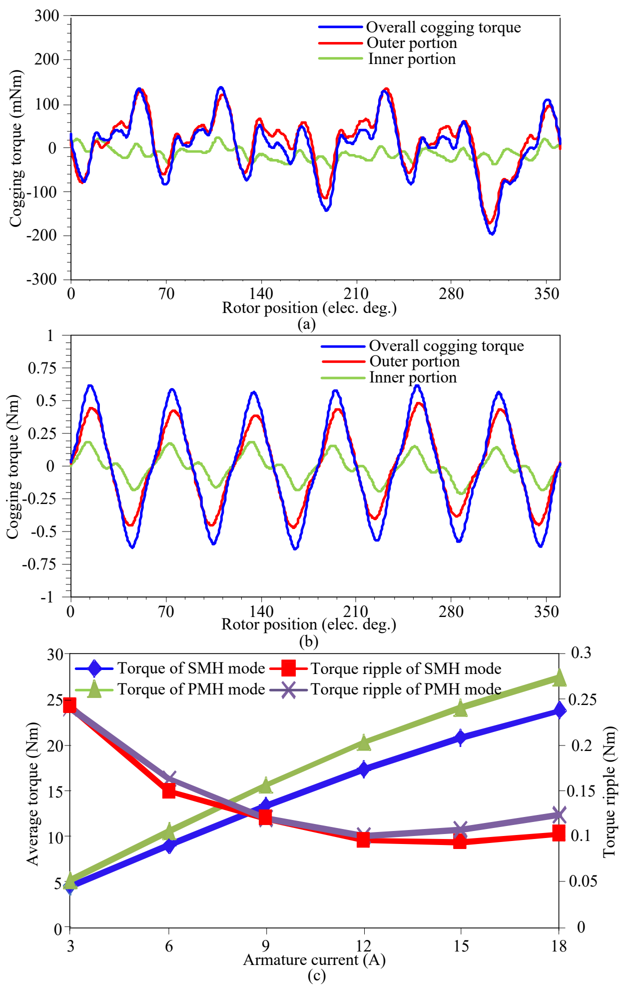

Fig. 10. Torque performances. (a) Cogging torque in PMH mode. (b) Cogging torque in SMH mode. (c) Average output torque and its torque ripple.

C. Demagnetization Analysis

Due to the low coercivity of the FPM, the irreversible demagnetization is likely to occur in the load operation, and thus it is important to analyze the partial demagnetization of the FPM. Fig. 11 (a) shows the flux density of the FPM in one electrical-cycle at the situations of no-load, on-load and overload. It indicates that there is no full demagnetization both in the PMH mode and SMH mode, even under the overload operation. Meanwhile, the operation points of the FPM in one electrical-cycle are shown in Fig. 11 (b). It can be seen that the PM operation point in SMH mode are higher than it in PMH mode among the three situations. In order to obtain the intuitionistic results, the field distributions at the situations of on load and overload are shown in Fig. 12. It demonstrates that there is no demagnetization in SMH mode at the on-load situation, while the partial demagnetization can be found in PMH mode. So, whether the FPM in PMH mode or in SMH mode, the partial demagnetization can be found at the overload situation. Hence, the C-HPMFS motor in SMH mode exhibits stronger resistance to the demagnetization.

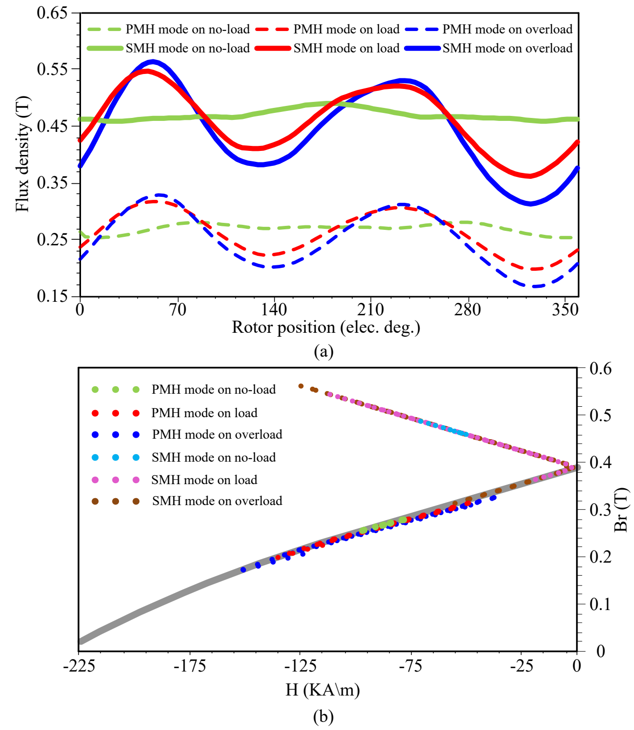

Fig.11. The flux density and operation points of FPM in one electrical-cycle. (a) FPM flux density. (b) FPM operation points.

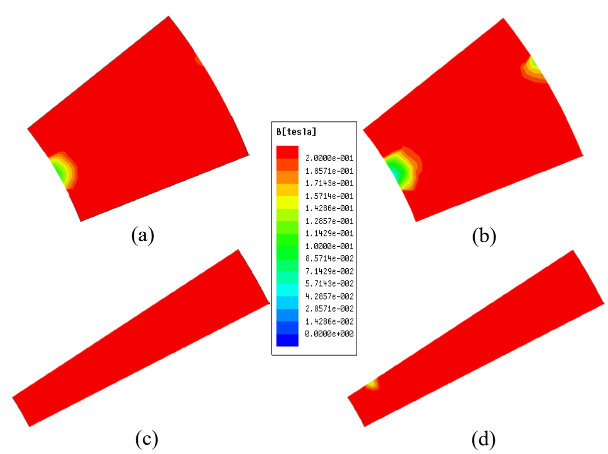

Fig.12. Irresistible demagnetization region. (a) FPM in PMH mode on load. (b) FPM in SMH mode on load. (c) FPM in PMH mode on overload. (d) FPM in SMH mode on overload.

V. CONCLUSION

In this paper, a compound rotor flux switching motor with two topologies of HPM were proposed to reduce the volume of NdFeB and improve magnet usage efficiency. Moreover, the multi-objective optimization design was conducted for the proposed motor, contributing to obtaining the optimal motor performances. The main conclusions of the study can be summarized as follows:

1) By the co-working of the different excitation sources which consist of NdFeB and ferrite, the proposed motor can not only realize the significant reduction of the NdFeB volume, but also offer a competitive output torque.

2) Combined with the design concepts of compound rotor and no stator yoke, the proposed motor possesses an increased PM usage efficiency by effectively utilizing the external magnetic flux leakage.

3) By purposely utilizing the methods RSM and SNP, the multi-objective optimization design is conducted effectively for the proposed motor. And the optimization results are verified by the electromagnetic performance analysis.

In conclusion, due to the competitive motor performances and effective cost reduction, the proposed motor presents the potential application prospect in electric vehicles.

REFERENCES

[1] M. Cheng, P. Han, and W. Hua, "General airgap field modulation theory for electrical machines," *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6063-6074, Aug. 2017.

[2] X. Zhu, Z. Xiang, C. Zhang, L. Quan, Y. Du, and W. Gu, "Co-reduction of torque ripple for outer rotor flux-switching PM motor using systematic multi-level design and control schemes," *IEEE Trans. Ind. Electron.*, vol. 64, no. 2, pp. 1102-1112, Feb. 2017.

[3] X. Zhu, D. Fan, L. Mo, Y. Chen, and L. Quan, "Multi-objective optimization design of double-rotor flux-switching permanent magnet machine considering multi-mode operation," *IEEE Trans. Ind. Electron.*, DOI 10.1109/TIE.2018.281864, 2018.

[4] H. Yang, Z. Q. Zhu, H. Lin, P. L. Xu, H. L. Zhan, S. Fang, and Y. Huang, "Design synthesis of switched flux hybrid-permanent magnet memory machines," *IEEE Trans. Energy Convers.*, vol. 32, no. 1, pp. 65-79, Mar, 2017.

[5] Z. Xiang, X. Zhu, L. Quan, Y. Du, C. Zhang, and D. Fan, "Multilevel design optimization and operation of a brushless double mechanical port flux-switching permanent-magnet motor," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6042-6054, Oct. 2016.

[6] Z. Q. Zhu, J. T. Chen, "Advanced flux-switching permanent magnet brushless machines," *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 1447-1453, Jun. 2010.

[7] X. Zhu, Z. Shu, L. Quan, Z. Xiang, and X. Pan, "Design and multi-condition comparison of two outer-rotor flux-switching permanent magnet motors for in-wheel traction applications," *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6137-6148, Aug. 2017.

[8] H. Yang, H. Lin, Z. Q. Zhu, D. Wang, S. Fang, Y. Huang, "A variable-flux hybrid-PM switched-flux memory machine for EV/HEV applications," *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2203-2214, May/Jun, 2016.

[9] Z. Z. Wu and Z. Q. Zhu, "Analysis of air-gap field modulation and magnetic gearing effects in switched flux permanent magnet machines," *IEEE Trans. Magn.*, vol. 51, no. 5, article number: 8105012, May. 2015.

[10] M. Cheng, P. Han, G. Buja, and M. G. Jovanović, "Emerging multi-port electrical machines and systems: past developments, current challenges and future prospects," *IEEE Trans. Ind. Electron.*, DOI 10.1109/TIE.2017.2777388, 2017.

[11] X. Zhu, X. Wang, C. Zhang, L. Wang, and W. Wu, "Design and analysis of a spoke-type hybrid permanent magnet motor for electric vehicles," *IEEE Trans. Magn.*, vol. 53, no. 11, article number: 8208604, May. 2017.

[12] 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.

[13] G. Zhang, W. Hua, M. Cheng, and J. Liao, "Design and comparison of two six-phase hybrid-excited flux-switching machines for EV/HEV applications," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 481-493, Jan. 2016.

[14] D. Kim, H. Hwang, S. Bae, and C. Lee, "Analysis and design of a double-stator flux-switching permanent magnet machine using ferrite magnet in hybrid electric vehicles," *IEEE Trans. Magn.*, vol. 52, no. 7, article number: 8106604, May. 2017.

[15] X. Zhu, Z. Xiang, L. Quan, W. Wu, and Y. Du, "Multi-mode optimization design methodology for a flux-controllable stator permanent magnet memory motor considering driving cycles," *IEEE Trans. Ind. Electron.*, vol. 65, no. 7, pp. 5353-5366, Nov. 2017.

[16] X. Zhu, Z. Xiang, L. Quan, Y. Chen, and L. Mo, "Multi-mode optimization research on a multi-port magnetic planetary gear permanent magnet machine for hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, DOI 1 10.1109/TIE.2018.2813966, 2018.

[17] G. Lei, J. Zhu, and Y. Guo, "Multidisciplinary design optimization methods for electrical machines and drive systems," Springer-Verlag Berlin Heidelberg, 2016.

[18] X. Zhao, and S. Niu, "Design and Optimization of a New Magnetic-Geared Pole-Changing Hybrid Excitation Machine," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9943-9952, Dec. 2017.

[19] G. Lei, T. S. Wang, J. G. Zhu, Y. G. Guo, and S. H. Wang, "System-level design optimization method for electrical drive systems-robust approach," *IEEE Trans. Ind. Electron.*, vol. 62, no. 8, pp. 4702-4713, 2015.

[20] G. Lei, T. S. Wang, J. G. Zhu, Y. G. Guo and S. H. Wang, "System level design optimization method for electrical drive systems-deterministic approach," *IEEE Trans. Ind. Electron.,* vol. 61, no. 12, pp. 6591-6602, Dec. 2014.

[21] B. Ma, G. Lei, J. G. Zhu, Y. G. Guo and C. C. Liu, "Application-oriented robust design optimization method for batch production of permanent-magnet motors," *IEEE Trans. Ind. Electron*, vol. 65, no. 2, pp. 1728-1739, 2018.

[22] G. Lei, J. Zhu, Y. Guo, C. Liu and B. Ma, "A review of design optimization methods for electrical machines", *Energies*, vol. 10, no. 12, Art. no. 1962, pp. 1-31, 2017.

[23] G. Lei, C. C. Liu, J. G. Zhu, and Y. G. Guo, "Techniques for multilevel design optimization of permanent magnet motors," *IEEE Trans. Energy Convers.*, vol. 30, no. 4, pp. 1574-1584, Nov. 2015.

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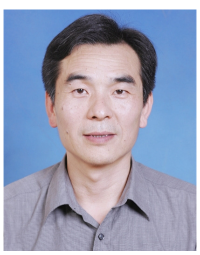

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