

Design and Shape Optimization of Permanent Magnet Synchronous Machine with Hybrid Stator Cores

Shiwei Zhang¹, Chengcheng Liu¹, *Member, IEEE*, Gang Lei², *Senior Member, IEEE*, Youhua Wang¹, and Jianguo Zhu³, *Senior Member, IEEE*

¹State Key Laboratory for Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin, 300130, China, 985646120@qq.com, 2016020@hebut.edu.cn, wangyi@hebut.edu.cn.

²School of Electrical and Data Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia, gang.lei@uts.edu.au.

³School of Electrical and Information Engineering, University of Sydney, Sydney, NSW 2006, Australia, jianguo.zhu@sydney.edu.au.

Amorphous alloys show great potential for application in the stator of electric machines due to their low iron loss characteristics. However, Amorphous alloys have a low saturation density and are prone to density saturation under high load conditions, which limits the performance of the machine. In this paper, a stator structure with a hybrid core of amorphous alloy and silicon steel is proposed to balance low iron loss and high load performance. Meanwhile, a polynomial method is used to establish the shape of the splices of the hybrid core material and to explore the effect of the geometry of the splices on the performance of the machine. Moreover, an agent model based multi-objective optimization approach is used to optimize the spliced structure to address the difficulty of optimization due to the large number of shape parameters at the splices. The results show that hybrid core machines are optimized to reduce the reluctance and improve the flux distribution to improve the machine performance compared to amorphous alloy stator machines. Finally, a prototype was built and the significant effect of the optimized hybrid core structure in enhancing the performance of the machine was experimentally verified.

Index Terms—amorphous alloy, hybrid stator cores, permanent magnet synchronous machine (PMSM), shape optimization, agent model.

I. INTRODUCTION

IN recent years, amorphous alloys have attracted a lot of attention due to their excellent soft magnetic properties, especially low core loss characteristics. The unique characteristics make their application in energy-efficient machines very promising since reducing iron losses is the key to achieving higher performance and energy savings [1]. However, an inherent limitation of amorphous alloys is their low saturation flux density. This drawback leads to flux saturation at high load conditions and limits the torque generation and overall performance of the machine. Therefore, it is critical to address this challenge to unlock the full potential of amorphous alloy materials in machine design.

Some studies have shown that hybrid core structures can significantly improve the performance of machines [2-3]. The design of Hybrid core combining amorphous alloys with silicon steel have emerged as a potential solution to alleviate the limitations of amorphous alloys. Silicon steel has a high saturation flux density that complements the low loss characteristics of amorphous alloys. By utilizing the advantages of both materials, hybrid cores aim to achieve a balance between low core losses and improved performance under high load conditions. However, the integration of these two materials also poses a number of challenges, particularly at the joints, where magnetic and mechanical properties may be adversely affected due to geometric and material mismatches.

In this paper, a new hybrid stator core structure consisting of an amorphous alloy and silicon steel (Hybrid-PMSM) is proposed. Meanwhile, a polynomial based modelling approach

is used to build and design the geometry of the joint between the two materials. Moreover, the effect of joint shape on the overall magnetic performance of the machine is systematically investigated. An agent model based multi-objective optimization approach is employed to optimize the shape parameters to reduce the optimization time due to the numerous parameters involved in optimizing the geometry at the hybrid core contact. Finally, a prototype of permanent magnet synchronous machine (PMSM) was fabricated, and experimental validations are performed. The results demonstrate the efficacy of the proposed method and design in achieving significant performance improvements.

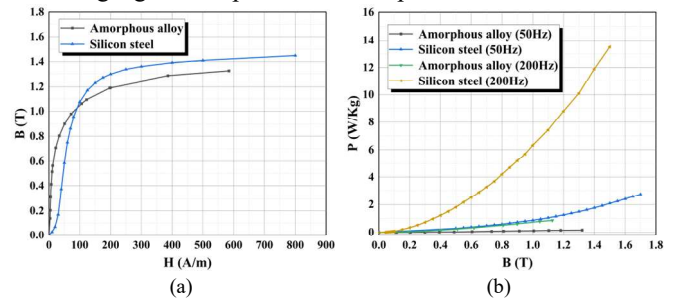


Fig.1. Magnetic properties of amorphous alloys and silicon steel material, (a) magnetization curves, (b) iron loss curves.

II. MAGNETIC PROPERTIES OF SOFT MAGNETIC MATERIALS AND TOPOLOGY OF PROPOSED PMSM

A. Comparison of Amorphous alloys and silicon steel

The magnetic properties of amorphous alloy and silicon steel used for designing PMSMs are measured based on the ring sample method. Fig. 1(a) shows the magnetization curves of

both materials and it can be seen that the permeability of amorphous alloy is higher than that of silicon steel, but its saturation density is lower. Hence, amorphous alloy materials used in the design of machines can degrade the performance of machines under high load conditions. Meanwhile, the iron loss of amorphous alloy at different frequencies is much lower than that of silicon steel as shown in Fig. 1(b). Therefore, the reasonable use of amorphous alloy and silicon steel hybrid core structure can improve the output performance and efficiency of the machine under high load conditions while reducing the iron loss.

B. Structure of PMSM and proposed hybrid stator core

Fig. 2 (a) shows the topology of PMSM, where the stator is made of amorphous alloy material. The characteristic of loss significantly reduces the iron loss in the stator part and improves the efficiency of the PMSM. However, the saturation magnetic density of amorphous alloys is lower than that of silicon steel, which limits the machine performance due to the easy saturation of the stator. Fig. 2 (b) shows the structure of the proposed Hybrid-SynRM, where the specifications of both rotors of PMSM remain identical. Especially, the stator core is made of a mixture of amorphous alloy and silicon steel, with silicon steel mixed in the easily saturated parts such as the stator shoes and teeth. The saturation level of the stator is reduced due to the high magnetic density of silicon steel. Therefore, the performance of the PMSM is further improved.

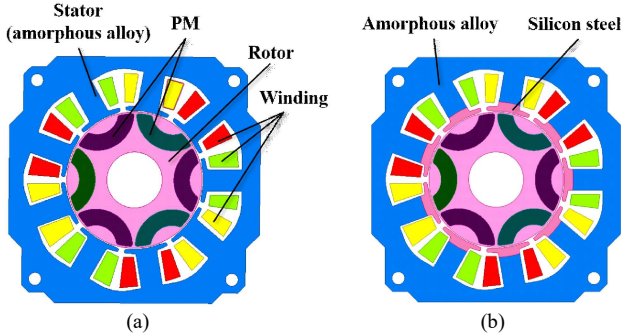


Fig.2. (a) Topology of PMSM, (b) Hybrid-PMSM.

III. SHAPE DESIGN OF SPLICES AND EXPERIMENTAL VERIFICATION

A. Shape design of hybrid core splice

The geometric shape of the joint of the hybrid magnetic core structure has a significant impact on performance of the PMSM. Reasonable design of the joint shape can improve the distribution of magnetic flux, effectively reduce magnetic resistance, and enhance the overall performance. In this paper, the shape of the joint was established using polynomial modeling method, and different geometric shapes are determined by some curves of the following equation,

$$y_i = a_i + b_i x_i + c_i x_i^2 + d_i x_i^3, \quad i = 1, 2, \dots, n \quad (1)$$

where a_i to d_i are coefficients, x_i and y_i are horizontal and vertical coordinates, and i is the number of curves. Fig. 3 shows the stator structure determined using the proposed polynomial method with different parameters.

Since shape optimization involves complex problems with multiple objectives and parameters, traditional optimization methods are computationally expensive and slow to converge. Therefore, the multi-objective optimization method based on the agent model is employed to optimize the design of the spliced structure, which significantly reduces the complexity of the optimization calculation.

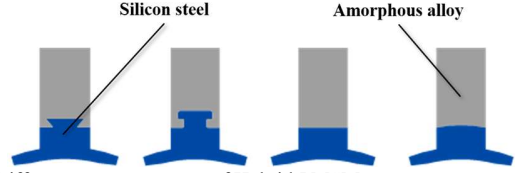


Fig. 3. Different stator structures of Hybrid-PMSM.

B. Experimental results

Fig. 4 (a) shows the prototype and the experimental platform. Meanwhile, the electromagnetic performance of PMSM is tested. Fig. 4 (b) shows the comparison of the output torque of two PMSMs with current density. It can be seen that the hybrid-PMSM has a higher output torque as the current density increases, which is due to the use of silicon steel reducing the saturation level of PMSM. The results validated the effectiveness of the proposed method.

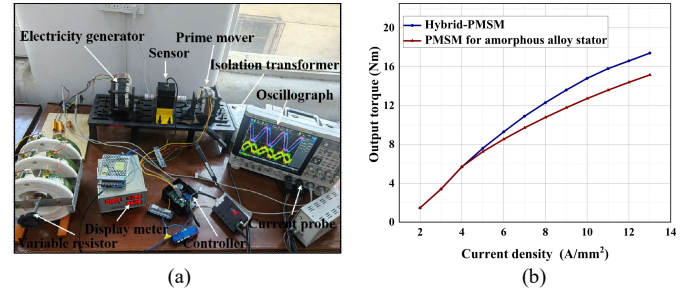


Fig. 4. (a) Experimental platform, (b) comparison of output torque.

IV. CONCLUSION

In this paper, the machine design scheme based on a hybrid core structure of amorphous alloy and silicon steel is proposed to effectively balance the contradiction between low iron loss and high load performance. Meanwhile, the polynomial method is used to establish the geometric model of the splices, and the influence of the shape of the hybrid core splices on the performance of the machine is thoroughly investigated. Moreover, an agent model based multi-objective optimization approach was used to optimize the splicing structure. Compared to the amorphous alloy stator, the results show that the optimized hybrid core structure improves the output performance and efficiency of machine at high load conditions.

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