

Optimal design of Permanent magnet assisted synchronous reluctance motor considering mechanical stiffness

Su-Min Kim¹, Woo-Sung Jung¹, Manh-Dung Nguyen¹, Duy-Tinh Hoang¹, Dae-Joon You², Kyung-Hun Shin³, and Jang-Young Choi¹

¹Department of Electrical Engineering, Chungnam National University, Daejeon 34134, South Korea

²Department of Fire Safety Engineering, Chungnam State University, Cheongyang-gun 33303, South Korea

³Department of Electrical Engineering, Changwon National University, Changwon 51140, South Korea

This paper proposes a design for a permanent magnet assisted synchronous reluctance motor (PMA-SynRM) with a focus on mechanical robustness. Permanent Magnet Synchronous Motors (PMSMs) are widely used for their high performance and efficiency, achieved through the use of rare-earth permanent magnets. However, the use of rare-earth magnets poses economic challenges in terms of motor design and maintenance. To address this, research is being conducted on PMSM designs that incorporate non-rare-earth materials. The PMA-SynRM is a variation of the Synchronous Reluctance Motor (SRM) that uses non-rare-earth permanent magnets in the rotor to improve power factor and output. Consequently, PMA-SynRM requires a multi-layer arrangement of permanent magnets, which complicates miniaturization and introduces vulnerabilities to stress. This paper analyzes the correlations between design variables affecting both electromagnetic performance and stiffness, using optimization algorithms. The findings of this study are expected to be valuable for selecting critical design parameters in the initial design of PMA-SynRM.

Index Terms — Mechanical stiffness, Flux barrier, Optimization, Permanent magnet assisted synchronous reluctance motor

I. INTRODUCTION

The rare-earth permanent magnets result in economic disadvantages in terms of motor design and maintenance. As a result, research into Permanent magnet synchronous motor (PMSM) designs using non-rare-earth materials is being actively pursued across various industrial sectors [1,2].

The Permanent Magnet Assisted Synchronous Reluctance Motor (PMA-SynRM) is a variation of the Synchronous Reluctance Motor (SRM) that uses multiple layers of non-rare-earth permanent magnets in the rotor to enhance the power factor and output. However, it faces the issue of reduced performance compared to PMSMs using rare-earth permanent magnets of the same size. Therefore, the PMA-SynRM with non-rare-earth magnets requires a multi-layer arrangement of permanent magnets. This, however, introduces challenges in miniaturization and leads to several vulnerabilities, such as increased susceptibility to stress. To address these challenges, selecting and analyzing design variables that significantly influence electromagnetic performance is crucial in the initial design.

In this paper, two rotor geometries of the PMA-SynRM were compared and optimized for design. The general segment-shaped rotor and the fluid-shaped rotor geometry, based on the Joukowski airfoil potential formulation, were designed under the same conditions and compared in performance using FEM. In addition, the correlation between design variables is analyzed using an optimization algorithm to achieve a robust design for stiffness.

II. PMA-SYNRM OPERATING PRINCIPLE

Figure 1 (a) shows the conventional PMA-SynRM model, and (b) shows the fluid shape. In Figure 2, (a) and (b) are vector diagrams of SRM and PMA-SynRM, respectively. The operating principle of PMA-SynRM is compared with the conventional SRM vector diagram [3].

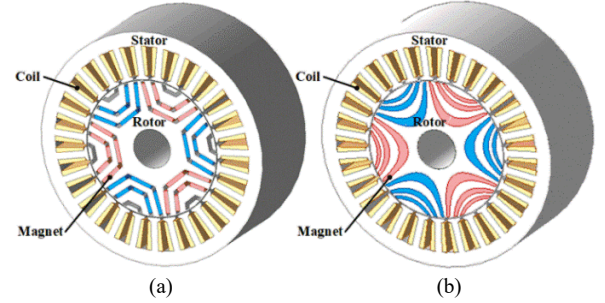


Fig. 1. Conventional PMA-SynRM: (a) Segment-shaped rotor; (b) Fluid-shaped rotor.

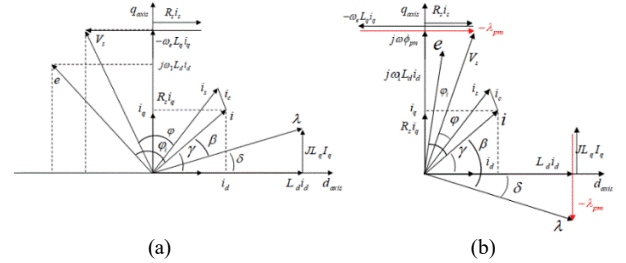


Fig. 2. Vector diagram of (a) SRM, (b) PMA-SynRM

$$\lambda_d = L_d i_d, \quad \lambda_q = L_q i_q + \lambda_{pm} \quad (1)$$

$$T_e = \frac{3}{2} \frac{P}{2} [(L_d - L_q) i_q i_d + \lambda_{pm} i_d] \quad (2)$$

The current phase angle that generates the maximum torque of PMA-SynRM lies in the first quadrant. As a result, the current values of both the d-axis and q-axis are positive. The resulting flux linkage expressions for the d-q axis of PMA-SynRM are given by (1). L_n , i_n are the inductance and current about the d-axis and q-axis, respectively. Since the permanent magnet blocks the q-axis flux path of the SRM, the torque of the PMA-SynRM, as shown in (2), is defined [4].

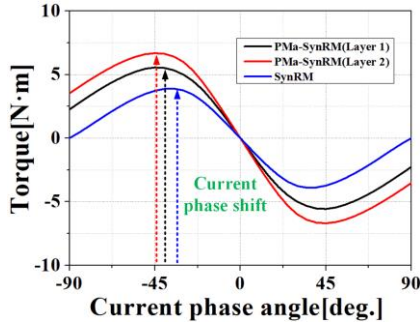


Fig. 3. Motor output comparison between SRM and 1-layer and 2-layer PMA-SynRM.

As shown in Table 2, when the permanent magnets are arranged in multiple layers along the q-axis flux path, the q-axis inductance decreases. This behavior is further confirmed in Figure 3, where it is observed that the current phase angle decreases while the torque increases simultaneously. In other words, both the power factor and output are improved.

TABLE II
COMPARISON OF D-Q AXIS INDUCTANCE IN ROTOR FERRITE PM ARRANGEMENT

Parameter	Unit	SynRM	Layer1 PMA SynRM	Layer2 PMA- SynRM
d-Axial inductance	[mH]	3.50	3.33	3.3
q-Axial inductance	[mH]	2.02	1.36	1.08

III. FLUID SHAPE OF THE FLUX BARRIER

First, the magnetic flux lines inside the rotor of PMA-SynRM are derived via the Joukowski function (3), (4) [5].

r and θ are polar coordinates (radius and angle), p is the number of pole pairs in the machine, and S_r is the radius of the shaft. C_n is a method for defining the magnetic flux lines. A detailed explanation of the geometry through the magnetic flux density of the barrier layer through the magnetic equivalent circuit is covered in the full paper.

$$r(\theta) = (s_r) \cdot \sqrt[p]{\frac{C_n + \sqrt{C_n^2 + 4 \cdot \sin^2(p\theta)}}{2 \cdot \sin(p\theta)}} \quad (3)$$

$$C_n = \frac{\sin(p\theta) \cdot \left[\left(\frac{r_n}{s_r} \right)^{2p} - 1 \right]}{\left(\frac{r_n}{s_r} \right)^p} \quad (4)$$

IV. SENSITIVITY ANALYSIS OF ROTOR DESIGN VARIABLES

Figure 4 illustrates the design variables based on the rotor shape. The stiffness is significantly influenced by the thickness of the rib, core, and permanent magnets, as well as the number of layers. As shown in Figure 5(a), the stiffness is most strongly affected by the angle of the first layer. Furthermore, Figs. 5(b) and (c) indicate that a proper adjustment of the first-layer angle can lead to improvements in both torque ripple and power factor.

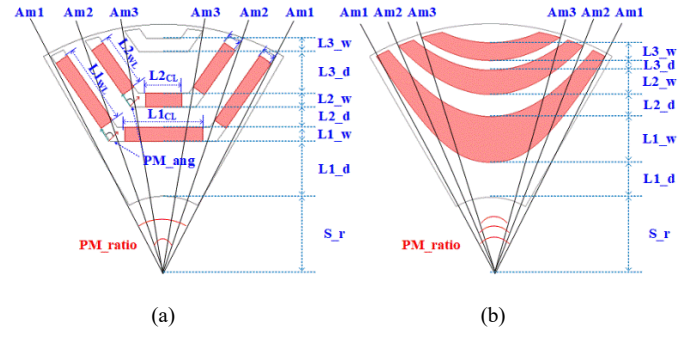


Fig. 4. PMA-SynRM rotor design variables: (a) segments; (b) fluid.

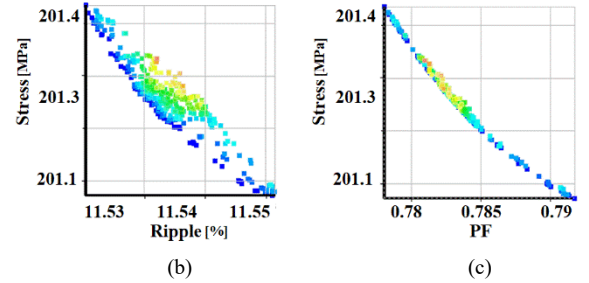
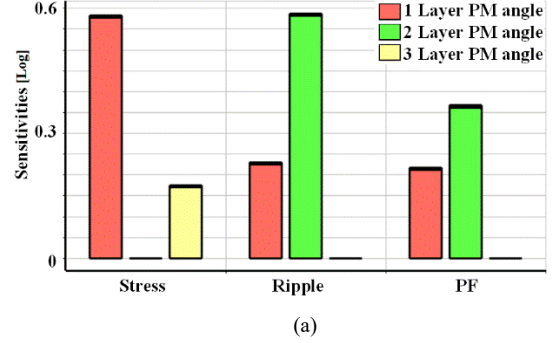


Fig. 5. Sensitivity analysis considering stiffness: (a) Analysis by layer number, (b) ripple and (c) power factor according to the angle of 1 layer

V. CONCLUSION

This paper presents the optimal design of the PMA-SynRM, considering both electromagnetic performance and mechanical stiffness. It is expected that this approach will significantly simplify rotor shape design using the magnetic equivalent circuit and address the stiffness vulnerabilities of the rotor.

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