Effect of Structure Parameters on the Losses and Efficiency of Surface-Mounted PMSM

Rui Yang, Chengming Zhang*, Mingyi Wang, Liyi Li

Abstract – Due to the advantages of high efficiency and high torque density, the Permanent Magnet Synchronous Machine (PMSM) has been widely used in direct-drive applications such as all-electric propulsion system. The loss and efficiency of PMSM are the main restriction for performance improvement. This paper focuses on analyzing the influence of structure parameters on the loss and efficiency of PMSM, including the split-ratio, the thickness of PMs, the pole-slot combination and the utilization of Halbach PM array, based on the Magnetic Circuit Method (MCM). The variation of the loss with the changing of parameters can provide some guidance for high-efficiency motor design. And the results of Finite Element Analysis (FEA) prove the correctness of MCM.

Index Terms—Permanent Magnet Synchronous Machine, loss and efficiency, split ratio, pole-slot combination, Halbach array.

I. NOMENCLATURE

A Electric load
$A_h$ Slot area
$B_{d}$ Air gap flux density
$b_1$ Stator tooth width
$b_{t1}$ Stator slot top width
$b_{t2}$ Stator slot bottom width
$h_1$ Stator tooth body height
$h_{t}$ Stator tooth height
$K_{s}$ Stator core stack factor
$t$ Stator tooth pitch
$D_{r}$ Stator bore diameter
$D_{o}$ Stator outer diameter
$S_{f}$ Slot fill factor
$t_{o}$ Stator split ratio
$t_{th}$ Stator slot open width

II. INTRODUCTION

Permanent magnet synchronous machine has been widely used in industry applications due to its advantages of high efficiency, high torque density and high reliability. In the area of limited energy consumption such as solar powered air vehicles, the motor efficiency improvement has become a challenging problem.

The influence of split ratio on the output torque of Surface-Mounted Permanent Magnet Synchronous Machine (SPMSM) has been analyzed under the condition of constant copper losses in [1]. In [2], the effect of split ratio on the copper losses of interior PMSM has been conducted from the relationship between the structure parameters and electromagnetic parameters based on the open slot machine model. The relationship among torque density and split ratio has also been studied in [3] for the outer rotor brushless DC motors. Though many researchers have concluded the influence of split ratio on the motor performance, there are still lack of results on how motor structure parameters can influence the loss and efficiency characteristic of motor.

This paper presents some detailed analysis process about the relationship between the stator split ratio and the copper losses. Then the effect of PM height, the different selection of pole-slot combination and the utilization of Halbach PM array will be conducted. Finally, the optimization results will be given to verify the correctness of the MCM and FEM.

III. 2-D ANALYSIS MODEL

The 2-D Finite Element Analysis (FEA) model of SPMSM and the simplified stator parameter optimization model are shown in Fig.1. (a) and (b) respectively. It comprises of stator core, three-phase balanced coils, PM and rotor core. The PMs are designed with arc-shape for its simple manufacture and installation. To make maximum utilization of the slot area, parallel stator teeth with equal width of the upper and bottom slot are designed. The basic specifications of the analysis model of SPMSM is shown in Table I.

![2-D FEA model](image1)

(b) Simplified stator parameters optimization model

Fig. 1. Analysis model of SPMSM

This work was supported in part by the Natural Science Foundation for Distinguished Young Scholars of China (51225702) and NSFC 51677041.

The authors are with the Department of Electrical Engineering and automation, Harbin Institute of Technology, Harbin 150001, China(e-mail: cmzhang@hit.edu.cn; liliyi.hit@gmail.com).
V. EFFECT OF PARAMETERS VARIATION ON LOSS AND EFFICIENCY

A. Stator Split Ratio

As for one of the basic design parameters of inner-rotor PMSM, the stator split ratio refers to the ratio of stator inner diameter to stator outer diameter, which has significant effect on the motor losses and efficiency capability [4].

In the analysis, the flux density in air gap, tooth and stator yoke remains approximately unchanged, thus the iron losses can be maintained in a small scale, according to that the volume of stator core changes very little. As can be seen in the Appendix, the relationship of motor copper losses with stator split ratio \( \lambda \) can be deduced as

\[ p_{Cu} = f(\lambda) \]  

under the condition that the stator stack length, slot fill factor, stator outer diameter and rated current remains quasi-constant for similar torque output.

\[ \text{Fig. 2. Motor performance v.s. split ratio} \]

According to the simplified analysis results, the curve between the coil area of every turn, the number of turns of every phase, the copper losses, current density and the split ratio has been shown in Fig. 2. As can be seen, the copper losses decrease with the split ratio at first and then increase. There exists a point in which the minimum copper losses can reach, where the split ratio range is around 0.6-0.7. The other three curves also prove the trend of copper losses.

B. PM Height

As for the source of magneto-motive force, the change of the PMs’ height will significantly influence the air gap flux density and so the iron losses. The electromagnetic torque can be expressed as

\[ T = 2D_{m}I_{p}K_{p}N_{ph}I_{y}B_{g} \]  

For motors with different PM, the number of series winding turns per phase \( N_{ph} \) changes inversely with the air gap flux density \( B_{g} \) for producing the same torque. It means the variation of PM height will influence the copper losses indirectly. In the process of analysis, the stator and rotor flux density can be invariant through adjusting the corresponding dimensions slightly, so the variation of iron losses can be neglected.

As shown in Fig. 3, the copper losses decrease significantly with the PM height and then increase slightly because the air gap flux density can be low when the PM height is too large or too small. As expected, the iron losses remain almost unchanged.

\[ \text{Fig. 3. Copper losses and iron losses varies with PM height under different pole-arc coefficient} \]

According to Fig. 4, the total losses has the same change trend as the copper losses due to its large variation with PM height. So there is an optimum value for PM height to reduce the motor losses, and the suitable range about this design is around 6.5-7.5mm. The results under MCM has also been verified by the FEM results with the pole-arc coefficient 0.92.

C. Pole-Slot Combination

The number of stator slots and rotor poles is an important machine design parameter, which can significantly influence the maximum machine efficiency under rated conditions [5]. Machine with fractional slot and concentrated winding has the advantage of small end winding and so the lower copper losses. The machine with distributed winding also has the merits of more sinusoidal back EMF, and so lower harmonic iron losses. The general used pole-slot combination include: \( Q=2p+2 \) and \( Q=2p+4 \), where \( Q \) and \( p \) are the slot and pole pair numbers respectively. For machine efficiency optimization, the following pole-slot combination has been selected and designed with the same stator inner and outer diameter, stator stack length and the similar stator and rotor flux density distribution: 4p12s (integral slot distributed

\[ \text{Fig. 4. Total losses vary with PM height under different pole-arc coefficient} \]
winding machine), 8p12s, 10p12s, and 14p12s (fractional slot concentrated winding machine).

As can be seen in Table II, the stator tooth width and the stator and rotor yoke height reduce with the number of poles increasing that will contribute to the increasing of slot area. Under the similar slot fill factor, large number of poles will make for larger winding cross section area and then lower TABLE II

| Main Design Parameters of Different Pole-Slot Combination |
|------------------------------|----------------|-----------------|-------------------|-----------------|
| Contents                    | 4p12s          | 8p12s           | 10p12s            | 14p12s          |
| SPP*                        | 1              | 0.5             | 0.4               | 0.4             |
| Kd1                         | 0.866          | 0.933           | 0.933             | 0.933           |
| stator tooth width/mm       | 8.4            | 8.1             | 7.8               | 5.4             |
| stator yoke height/mm       | 11.9           | 6.1             | 5.0               | 3.7             |
| rotor yoke height/mm        | 12.4           | 5.9             | 4.7               | 3.2             |
| conductors per slot         | 44             | 46              | 46                | 46              |
| turns & wire diameter/mm    | 9/0.47         | 9/0.6           | 10/0.6            | 12/0.6          |
| slot fill factor/%          | 76.9           | 75.1            | 76.7              | 74.6            |

*SPP: slots per pole per phase

phase resistance. It is observed that the stator and rotor yoke height obviously larger than the others, so to ensure suitable flux density distribution and proper slot fill factor, the wire diameter and the number of turns have to be reduced. So the copper losses of smaller pole number can be much higher, as shown in Fig. 5. It can be seen that the machine with combination of similar number of slots and poles and fractional slot concentrated winding can get lower total losses and higher efficiency.

D. Halbach PM Array

PMSM with Halbach PM array has the main merits as follows: thinner rotor yoke, more sinusoidal back EMF and lower harmonic iron losses and higher fundamental magnetomotive force[6]. The FEA model and the magnetizing direction of Halbach PM array is shown in Fig. 6 (a) and (b) respectively. The width ratio of the main magnet to the auxiliary magnet is defined as M:A in this paper. Considering the easiness of magnet manufacturing, the split ratio and PM height is designed as 0.6 and 6.5mm and the pole-slot combination is selected as 10p12s.

It can be seen from Fig. 7 that the utilization of Halbach PM array has large impact on the losses reduction compared with the general SPM Motor, with the reduction rate 11.8%. And the proper value of M:A is around 1.5:1.

E. Optimization Results

As given in section D, the simulation and analysis results of finally optimized motor parameters is given in Fig. 8. The FEA results show that the average iron losses is 18.2W, the average rotor eddy current losses is 3.1W, and the calculated copper losses is 52.8W, so the finally motor efficiency is 94.7%.
V. CONCLUSIONS

In this paper, the effect of several main machine structure parameters on the motor losses and efficiency has been studied, and the results can provide some guidance for high-efficiency PMSM design as follows:

1) Optimizing the stator split ratio design, and the optimal value is approximately around 0.65.
2) Optimum PM height exists for the copper losses reduction.
3) Proper selection of slot-pole combination with quasi-similar number, such as 14p12s for low power SPMSM, can reduce the losses much.
4) Utilization of Halbach PM Array with M:A around 1.5 can largely promote the motor efficiency.

The prototype machine has been manufactured but the detailed experiment results will be shown later.

VI. APPENDIX

According to Fig.1. (a), the stator core parameters can be deduced as follows based on the structure constraints:

\begin{align}
 b_{si} &= \frac{\pi(D_{a1}+2h_y)}{Q} - b_t \tag{A-1} \\
 b_{s2} &= \frac{\pi(D_{a1}-2h_y)}{Q} - b_t \tag{A-2} \\
 h_y &= \frac{D_{a1} - D_{a2} - 2h_u - 2h_y}{2} \tag{A-3} \\
 A_s &= \frac{b_{o1} + b_{o2} + h_y}{2} \tag{A-4} \\
 A_{cs} &= S_t A_s \tag{A-5} \\
 D_{a1} &= \lambda D_{a1} \tag{A-6} \\
 l_t &= \frac{\pi D_{a1}}{Q} \tag{A-7} \\
 \tau_t &= \frac{\pi D_{a1}}{2 \rho} \tag{A-8}
\end{align}

And then the stator tooth width and yoke height can be expressed by the air gap, tooth and yoke flux density as

\begin{align}
 b_t &= \frac{B_s}{K_r B_r} - l_t \tag{A-9} \\
 h_y &= \frac{\Phi_{g0}}{2L_k B_r} \tag{A-10}
\end{align}

in which

\begin{align}
\Phi_{g0} &= \frac{h_{o1} B_s A_s}{\sigma_0} = \frac{h_{o2} B_s}{\sigma_0} L_t \tau_t \alpha_r \tag{A-11}
\end{align}

is the air gap flux linkage.

So according to the above equations, the winding area can be deduced as the function of stator bore diameter, the ratio of air gap flux density to the tooth flux density $B_{s1}$, and the ratio of air gap flux density to the yoke flux density $B_y$

\begin{align}
 A_{cs} &= f_1(D_{a1}, \frac{B_s}{B_{s1}}, \frac{B_y}{B_r}) \tag{A-12}
\end{align}

With the same no load back-electromotive-force (EMF) and rated current, the output torque remain unchanged. The no load back EMF can be expressed with the stator bore diameter as follows:

\begin{align}
 E_0 &= \sqrt{2} \pi n_k N_{ph} \Phi_{g0} K_a \\
 &= \sqrt{2} \pi \frac{p n}{60} K_{g0} N_{ph} \frac{b_{o1} B_s}{\sigma_0} L_t \frac{\pi D_{a1}}{2 \rho} \alpha_r \frac{8}{\pi} \sin \left( \frac{\alpha_r \pi}{2} \right) \tag{A-13}
\end{align}

Substituting the $E_0$ with the rated phase voltage, the series turns of every phase can be deduced as

\begin{align}
 N_{ph} &= \frac{0.9E_0}{\sqrt{2} \pi n_k} \frac{b_{o1} B_s}{\sigma_0} L_t \frac{\pi D_{a1}}{2 \rho} \alpha_r \frac{8}{\pi} \sin \left( \frac{\alpha_r \pi}{2} \right) \tag{A-14}
\end{align}

It can be noted that $N_{ph}$ is only the function of stator bore diameter.

Combining the formula (A-12) and (A-14), coil area of every turn $A_{coil}$ is

\begin{align}
 A_{coil} &= A_{cs} Q = \frac{S_t Q}{m} f_1(D_{a1}, \frac{B_s}{B_{s1}}, \frac{B_y}{B_r}) \tag{A-15}
\end{align}

Neglecting the effect of end winding to the resistance, the phase resistance is

\begin{align}
 R_t &= \frac{2 \rho N_{ph} L_t}{A_{coil}} \tag{A-16}
\end{align}

And then the copper losses can be deduced as

\begin{align}
 p_{Cu} &= m i^2 R_t \\
 &= 2 \rho L_t i^2 \frac{m^2}{S_t Q} f_1(D_{a1})^2 \tag{A-17}
\end{align}

VII. REFERENCES

VIII. BIOGRAPHIES

Rui Yang was born in Hubei, China. He received the B.E. degree in electrical engineering from Harbin Institute of Technology (HIT), China, in 2015. He is currently working toward the Ph.D. degree in the Institute of Electromagnetic and Electronic Technology, HIT. His research interest is high-performance motion and motor drive control.

Chengming Zhang received the B.E., M.E., and D.E. degrees from the Harbin Institute of Technology (HIT), China, in 2005, 2007, and 2013, respectively. Since 2013, he has been a lecturer with the School of Electrical Engineering and Automation, HIT. His research areas include high efficiency motor systems, energy conversion and control.

Mingyi Wang was born in Jilin, China. He received the B.E., M.E., and Ph.D. degrees in electrical engineering from Harbin Institute of Technology (HIT), Harbin, China, in 2009, 2011 and 2016, respectively. He is currently with the Institute of Electromagnetic and Electronic Technology, HIT. His research interests include motor drive control, power electronic applications and magnetic levitation.

Liyi Li (M’09) received the B.E., M.E., and D.E. degrees from the Harbin Institute of Technology (HIT), Harbin, China, in 1991, 1995, and 2001, respectively. Since 2004, he has been a Professor with the School of Electrical Engineering and Automation, HIT. He has authored or coauthored more than 110 technical papers and is the holder of 50 patents. His research areas are in control and drive of linear motors, linear electromagnetic launch, accumulation of electric energy, and superconducting motors.