Design of the High Efficiency IPMSM considering the Operating Point with Different Characteristic

Soo-Gyung Lee
Department of automotive engineering
Hanyang University
Seoul, South Korea
sgar1109@hanyang.ac.kr

Min-Ro Park
minro1226@hanyang.ac.kr

Kyong-Soo Cha
chakungsoo@hanyang.ac.kr

Jae-Hyun Kim
zerg1258@hanyang.ac.kr

Jung-Pyo Hong
hongjp@hanyang.ac.kr

***Abstract*— This paper suggests a high efficiency design for an outer rotor type permanent magnet synchronous motor (PMSM). The key is to adopt a V-shaped interior permanent magnet synchronous motor (IPMSM) considering two operating points, where their characteristics are different. To derive directions in the motor design process, an outer rotor type surface permanent magnet synchronous motor (SPMSM) is analyzed. First, the loss is investigated, and the limitation of the SPMSM at the low speed operating point is presented. Then the influences of the circuit parameters on each efficiency are examined. From the analysis result, an outer rotor design having the permanent magnets arranged in V-shape is proposed in this paper. When the proposed shape is applied to the outer rotor type, the leakage bypass can be removed, and this can lead to the reduced leakage flux and increased linkage flux. By using the proposed rotor shape and changing core materials, the high efficiency of V-shaped IPMSM considering the different operating point is achieved.**

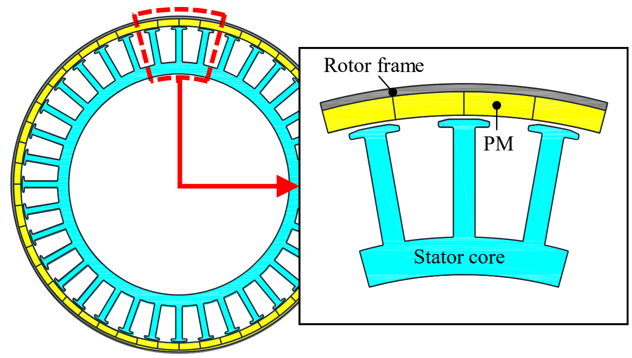
Keywords*— *Efficiency, operating point, outer rotor type permanent magnet synchronous motor

I. Introduction

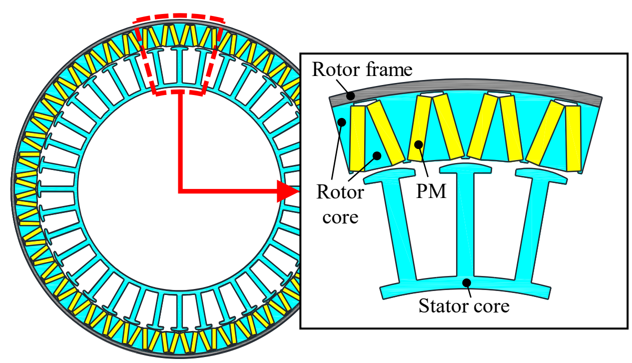
With increased demands for electric motors in industrial applications, PMSMs have widely used and studied due to their high torque density, high power density, and high efficiency [1]-[4]. In [5], it is shown that a proper shape of the permanent magnet (PM) enables to overcome the relatively low energy density of the rare-earth free magnet. [6] presents a wide constant power operation range was achieved by the segmented PMs.

For the outer rotor type, many researchers have focused on the surface mounted permanent magnet synchronous motors (SPMSM). In [7] and [8], the shape of the permanent magnets (PMs) is determined to improve the demagnetization characteristic, and the energy density, respectively. [9] shows that the energy consumption and the material cost is decreased, by using the amorphous stator core and optimizing a few design variables. In [10], the high efficiency design is accomplished, but the different characteristics according to the operating point are not considered. Those studies show that the outer rotor type SPMSM has less options for design variables in the design process. Furthermore, high efficiency design of an outer rotor type PMSM is rarely dealt in the existing researches.

First, the characteristics of the outer rotor type SPMSM in Fig. 1 are analyzed in this paper, according to its two different operating point: a low speed and a high speed operating point.



(a) SPMSM



(b) V-shaped IPMSM

Fig. 1. Configuration

From the analysis result, it is shown that there exists a structural limit in the outer rotor type SPMSM to improvement of the efficiency at the low speed. Then to obtain design directions, the influences of the circuit parameters on the efficiencies at each operating point are figured out. It is presented that increasing the linkage flux has great advantage for improving the efficiency at the low speed, while it can sacrifice the efficiency at the high speed because of the increased d-axis current to implement the flux-weakening.

To overcome the limit of the SPMSM, this paper suggests the V-shaped IPMSM in Fig. 1. And the improvements of the efficiencies at different operating points are discussed. By applying the V-shape PM arrangement to the outer rotor type,

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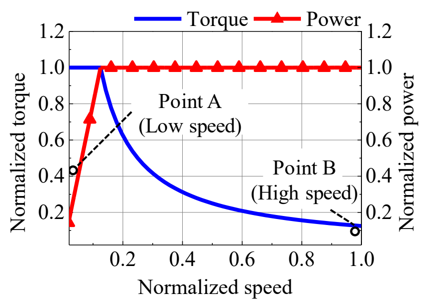


Fig. 2. Characteristic curve of the SPMSM

not only the PM usage can be increased but also the leakage flux can be reduced by eliminating leakage bypass. These advantages lead to the increase of the linkage flux. Then it is expected that the efficiency at the low speed is improved, while causing increase of the ohmic loss at the high speed. The increased ohmic loss at the high speed can be compensated by changing the core material, which has the reduced iron loss and the similar *B*-*H* characteristics compared to the conventional material, where *B* is the magnetic flux density and *H* is the magnetic field intensity.

To reduce the computational cost, a sensitivity analysis is conducted to determine the significant design variables to each efficiency. From the result, the significant design variables are selected for the multi-objective optimization considering the efficiencies at the two operating points. Then the high efficiency design of the V-shaped IPMSM is achieved. By fabricating and testing the back-electromotive force (BEMF), the design is verified.

II. Analysis of the SPMSM

The characteristic curve of the outer rotor type SPMSM is shown in Fig. 2, and it has two of operating points, the low speed point A and the high speed point B. The losses of the SPMSM at two different operating points are investigated based on the finite element analysis (FEA), while the ohmic and the iron loss are considered.

Then the limitation of the SPMSM at the low speed is presented. In a condition where the motor size, the air gap length, and the fill factor for stator coils are the same, the armature turns and the stator outer diameter can be varied for the modification of the configuration. Those small modification of the SPMSM makes a limitation for the improvement of the efficiency. To overcome the limitation, the rotor configuration is required to be changed.

Therefore, the influences of the circuit parameters are examined to derive design directions. From the result, the V-shaped PM arrangement is proposed in this paper. The proposed V-shaped PMs can not only increase the PM usage, but also remove the leakage bypass when applied to the outer rotor type. These advantages is helpful to improve the efficiency at the point A.

A. Efficiency and Loss

The efficiency map in Fig. 3 presents relatively lower efficiency in low speed operating region. The losses at each point are investigated as well. At the point A, the ohmic loss is the most loss. However, the ohmic loss is similar to the iron loss at the point B. These results show that the ohmic loss has to be reduced at the point A, while both the ohmic and iron loss should be decreased at the high speed point to improve each efficiency.

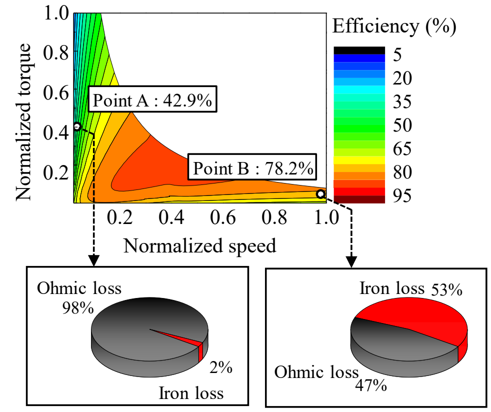


Fig. 3. Efficiency map and loss of the SPMSM

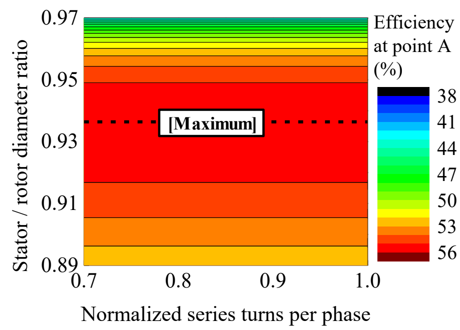


Fig. 4. Efficiency map and loss of the SPMSM

B. Limitation

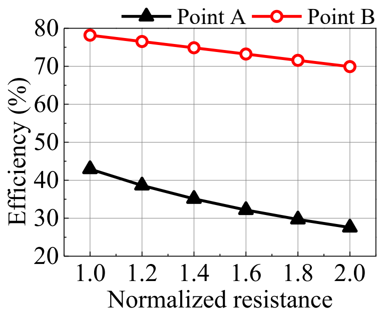
As the available modification of configuration is restrictive for the SPMSM, the limitation of the low speed efficiency exists. Fig. 4 shows the efficiency at the point A, depending on the armature series turns and the ratio of the stator and rotor outer diameter. The efficiency is estimated when the motor size, the air gap length, and the fill factor for the stator coils are constant. Also, it is assumed that the iron loss is proportional to the core volume.

The input current I_{rms} and the ohmic loss W_{ohm} is calculated as in (1)-(2), where P_{out} is the required output power, E_{rms} is the phase BEMF, and R_a is the phase resistance.

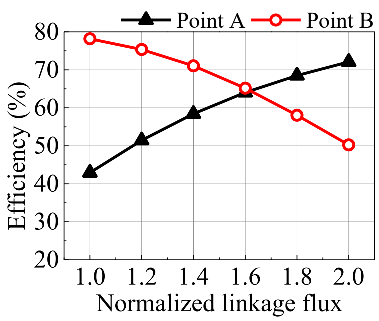
$$I_{rms} = \frac{P_{out}}{3E_{rms}} \tag{1}$$

$$W_{ohm} = 3R_a I_{rms}^{\ 2} \tag{2}$$

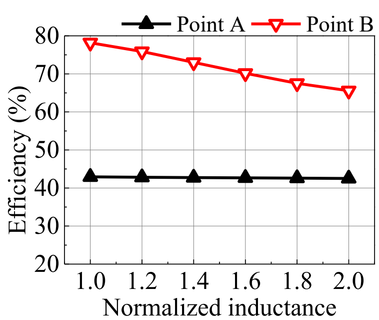
According the stator outer diameter and the series turns, the changed linkage flux causes the BEMF to change. This leads to the current change to obtain a constant output power. Also, the resistance is changed due to the variation of the coil length and the cross sectional area of the coil. When the stator diameter is increased having the same series turns, the PM usage is reduced, while the cross sectional area of the coil is increased. Thus, the current is increased and the resistance is



(A) Phase resistance



(b) Linkage flux



(c) Inductance

Fig. 5. Efficiency change according to circuit parameters

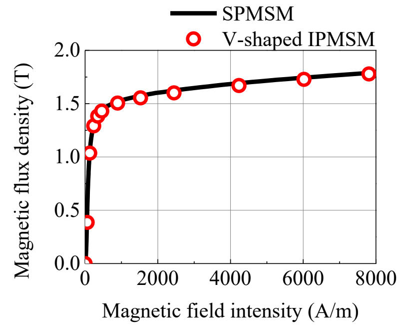
decreased at the same time. This makes an inflection point of the ohmic loss according to the stator outer diameter.

In contrast, the variation of the armature series turns in the same configuration has no influences on the ohmic loss. It is because that the current density is constant, despite of the varying turns.

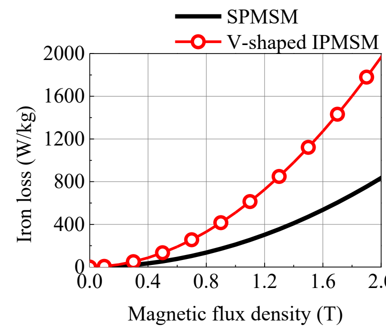
As a result, at the point A where the ohmic loss is much larger than the iron loss, improving the efficiency has a limit regardless of the configuration change of the SPMSM. To overcome the limit, this paper adopts a V-shaped PM arrangement. And the core material is changed to what has the smaller iron loss and the similar *B-H* characteristic compared with the conventional core.

C. Influences of the Circuit Parameters on Each Efficiency

The circuit parameters of a PMSM are those following: linkage flux, resistance, and inductance. Each parameter is calculated and used to analyze the characteristics of the PMSM, based on the FEA and the equivalent circuit method in [11]. Fig. 5 shows that the efficiencies at each of the point A and point B are varied with the circuit parameters. When the resistance is bigger, the large ohmic loss causes the efficiencies both at the point A and B to decrease.



(a) B-H characteristics



(b) B-H characteristics

Fig. 6. Characteristics of the used core materials

In case of the linkage flux, the tendencies according to the linkage flux are shown to be opposite at the point A and B. At the point A where the ohmic loss is the most, the efficiency is improved when the linkage flux is larger. This is because the current is decreased when the linkage flux is higher, which leads to a decreased ohmic loss, as previously explained in section II *B*. Whereas at the point B, the tendency is different from those at the point A. To reduce the voltage at the point B, the d-axis current is used for the flux-weakening control. The increased linkage flux leads to the increased d-axis current and the resultant large ohmic loss. Therefore, the efficiency at the point B is deteriorated.

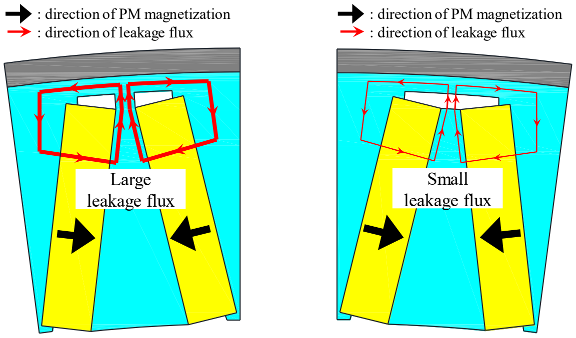
Unfortunately, as mentioned before, the SPMSM has a restrictive structure for varying the linkage flux. Therefore, this paper proposes the V-shaped arrangement of the PMs. Then the core is changed to a material that has the similar *B-H* characteristics and the smaller iron loss compared to the conventional core that used in the SPMSM. The characteristics of the core material are presented in Fig. 6.

From the above results, this paper uses following design directions to improve the each efficiency:

1) Smaller resistance

2) Larger linkage flux

3) Smaller iron loss



(a) Leakage bypass existing (b) Leakage bypass removed

Fig. 7. Comparison of leakage flux

III. Design of V-Shaped IPMSM

A. Proposed Rotor Configuration

From the analysis results of the section II, the rotor configuration with the PMs arranged in the V-shape is proposed in this paper. When the proposed configuration is applied to the outer rotor type PMSM, it can take advantages as following:

1) Increase of the PM usage

2) Structural stability

3) Elimination of the leakage bypass

Unlike the inner rotor type, where the core can be scattered when the large centrifugal force is applied, the core of outer rotor type where the centrifugal force is applied has structural stability.

Especially for the lower core part, the centrifugal force is applied with a direction toward the PMs. Thus, the scattering of the lower core can be prevented by the PMs. With those advantages, the leakage bypass can be removed and the leakage flux can be reduced as shown in Fig. 7.

The proposed rotor configuration having the V-shaped PM arrangement is illustrated in Fig. 8. By taking the advantages of both increasing PM usage and eliminating the leakage bypass, the large linkage flux can be obtained in the proposed design.

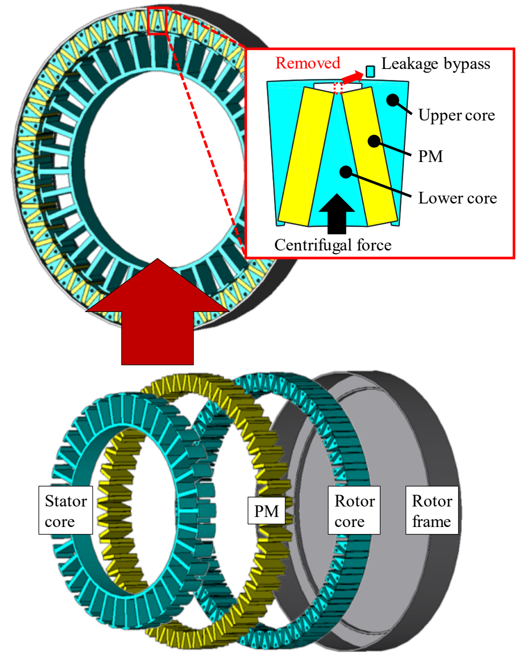


Fig. 8. Detailed configuration of the V-shaped PM arrangement

B. Sensitivity Analysis and Optimization

To reduce the computational cost, the design process is presented in Fig. 9, where the α represents the level of significance. The significant design variables are selected from the sensitivity analysis using the ANOVA. Among the available design variables of the proposed configuration, following 3 design variables are selected to have the significant influences on the efficiency at the point A and B:

1) Pole angle

2) Stator yoke thickness

3) Rotor chamfer

Then the multi-objective optimization considering each of the efficiencies is conducted with the significant design variables. The objective function is presented as in (3), where f is the objective function, w_A and w_B are the weighting factors of the efficiencies at the point A and B, respectively, and y_A and y_B are the normalized efficiencies at each point.

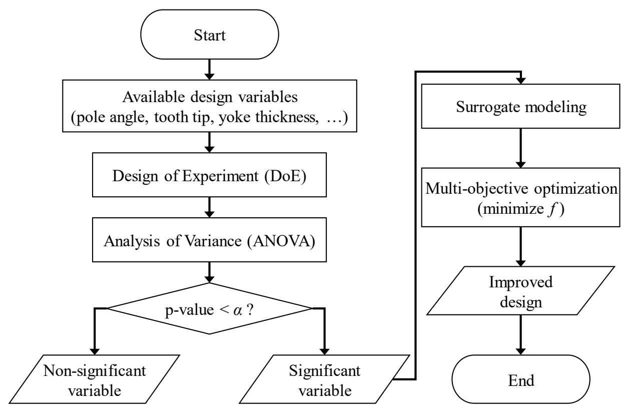


Fig. 9 Design process

$$f = -w_A y_A - w_B y_B \tag{3}$$

Depending on the weighting factors, the function is minimized and each efficiency is compared. Then the optimum design of the V-shaped IPMSM was selected based on the comparison result.

IV. Design Result and Comparison

Using the FEA, the characteristics of the V-shaped IPMSM are estimated and compared with those of the SPMSM. Compared to the SPMSM, the BEMF of the V-shaped IPMSM is increased by 19%, as shown in Fig. 10. This leads to the overall large increase of the efficiencies in the low speed region, while the efficiencies were slightly increased in the high speed region. The efficiency map is presented in Fig. 11. At the low speed operating point A, the efficiency is improved by 22.9%, and the efficiency at the high speed operating point B was slightly increased by 1.9%.

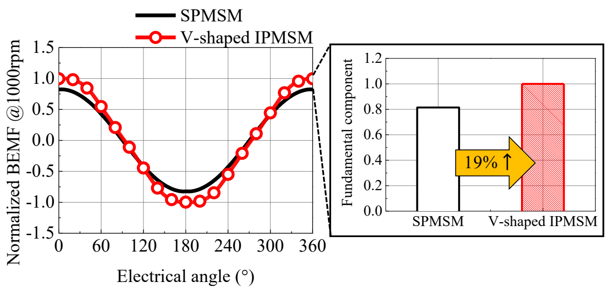
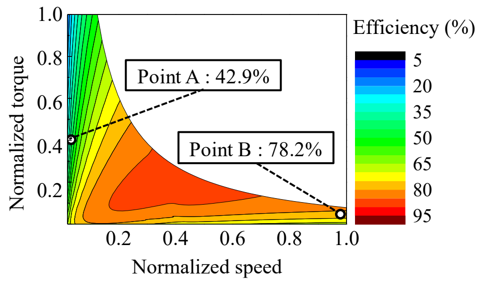
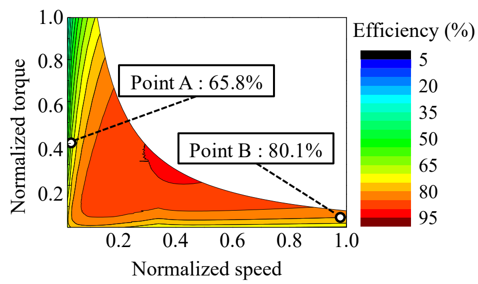


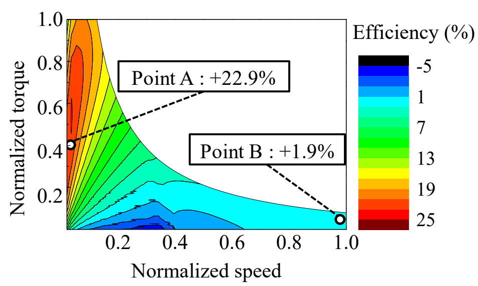
Fig. 10 Comparison of the BEMF at no-load condition



(a) SPMSM



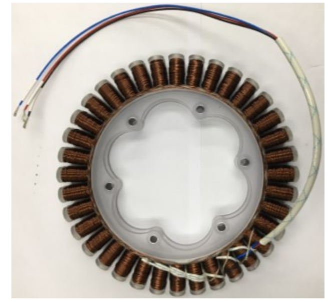
(2) V-shaped IPMSM



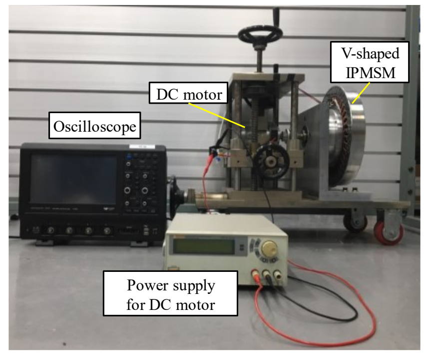
(c) Difference

Fig. 11 Comparison of the efficiencies between the SPMSM and the V-shaped IPMSM

(a) Rotor



(b) Stator



(c) Experimental composition

Fig. 12 Sample of the V-shaped IPMSM and the experimental composition.

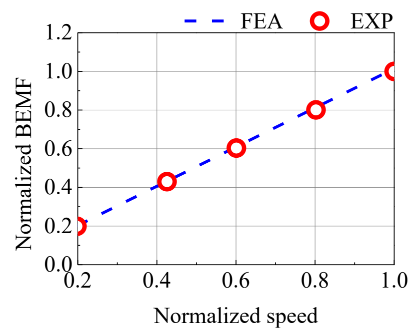


Fig. 13 Comparison of the BEMF of the V-shaped IPMSM

A sample of the V-shaped IPMSM is fabricated, as presented in Fig. 12. To verify the analysis result, the experiment for the BEMF is conducted with the experimental composition in Fig. 12. A dc motor is used for the sample to rotate and the BEMF is measured using the oscilloscope. According to the rotating speed, the measured BEMF is compared with the FEA results in Fig. 13. It is shown that the FEA results follow the experimental results well.

V. Conclusion

This paper suggests an appropriate configuration and its design process to improve the two point efficiencies of the outer rotor type PMSM. First, the outer rotor SPMSM is investigated and its loss is analyzed. The majority of the loss at the low speed operating point was the ohmic loss, while the ohmic loss and the iron loss are similar at the high speed point.

And the limitation of the SPMSM at the low speed point is revealed. To overcome the limitation and improve the efficiencies at each point, the influences of the circuit parameters on the efficiencies are examined at each point. Then the design directions for the improving the efficiencies are determined as smaller resistance, larger linkage flux, and smaller iron loss. Considering the directions, the V-shaped IPMSM is suggested. This is a suitable structure especially for the outer rotor type PMSM, because the core has structural stability when the rotor rotates.

To reduce the computational costs, design variables are classified into significant variables and non-significant variables using the sensitivity analysis. Through the sensitivity analysis considering the efficiencies at two different points, the significant design variables are used in the surrogate modeling for the multi-objective optimization. Then the optimums design for the V-shaped IPMSM is derived.

The experiment at no-load condition is conducted to verify the analysis result. According to the rotating speed, the analysis results are validated.

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