# Computational Method of Remanence Flux Density to Consider Overhang Effect in 2-D Analysis by Using Magnetic Energy

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**According to conventional study, it is possible to conduct two-dimensional (2-D) finite element analysis (FEA) that considers overhang effect through adjusted remanence flux density by applying overhang parameter. The latest study has found that overhang parameter can be obtained through variation of operating point of permanent magnet. In this study, we propose computational method to calculate remanence flux density accurately that considers overhang effect in 2-D FEA by using magnetic energy of permanent magnet. Proposed method is verified by comparison with results of three-dimensional FEA.**

***Index Terms*—Permanent magnet machines, permeance coefficient, energy product, magnetic energy.**

## I. Introduction

OVERHANG STRUCTURE of rotor has been applied to permanent magnet (PM) machine using ferrite in order to increase air-gap flux density while occupying the empty space in the rotor that is caused by stator end winding [1]. However, three-dimensional (3-D) finite element analysis (FEA) is required for performance analysis on motor with overhang structure [2]. It takes long computation time to perform 3-D FEA because the number of element node of 3-D model is larger than that of two-dimensional (2-D) model. In order to reduce the computation time, study on 2-D FEA that considers overhang effect has been conducted. By adjusting remanence flux density, it is possible to reflect the increment of air-gap flux density due to overhang structure in 2-D FEA. Previously, through experimental method and trial-and-error method, overhang coefficient was obtained, which reflects overhang effect [3], [4]. Since then, study on obtaining overhang coefficient through variation of PM's operating point without trial-and-error has been conducted [5]. In this paper, we propose computational method that calculates remanence flux density in view of magnetic energy of PM in order to consider PM overhang effect more accurately.

FEAs on both 3-D model with PM overhang and 2-D model without overhang were conducted. Through these analysis results, the remanence flux density that considers overhang effect can be calculated by applying proposed formula and we have conducted 2-D FEA, which uses calculated remanence flux density. Its validity is confirmed through comparison with 3-D FEA.

## II. Proposed Method

In case of motor with PM overhang structure, its PMs are partially exposed to air and thus the air gap in magnetic circuit becomes longer. As a result, the operating point of PM on demagnetization curve is shifted from point **a'** to **b'** as shown in Fig. 1(a) because the permeance coefficient of PM overhang model $P_{cOH}$ is lower than that of non-overhang model $P_c$.

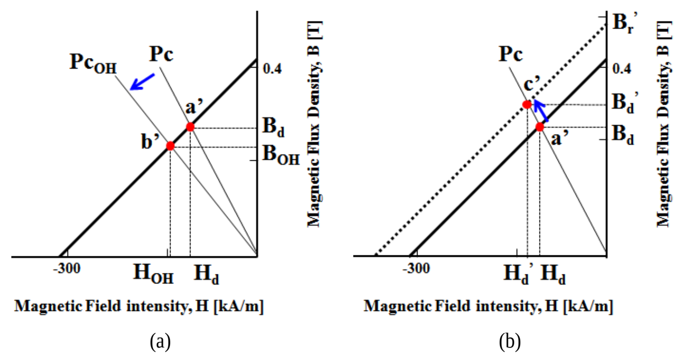



Fig. 1. Demagnetization curve and permeance coefficient. (a) Variation of permeance coefficient from non-overhang model to overhang model. (b) Shifted operating point due to increased remanence flux density in 2-D model.

It is possible to calculate energy product by using B and H on its operating point and we can finally calculate magnetic energy by multiplying energy product by volume of PM. Due to PM overhang, power density is increased since energy product of 3-D model is higher than that of 2-D model. In order to consider overhang effect in 2-D FEA, we increase remanence flux density and thus the operating point of 2-D model is shifted from point **a'** to **c'** in Fig. 1(b). Accordingly, not only its energy product but magnetic energy is also increased. Permeance coefficient of 2-D model is given by

$$P_c = -\frac{B_d}{\mu H_d} = -\frac{B'_d}{\mu H'_d} \qquad (1)$$

where $H_d$ and $B_d$ represent the value of coercive force and remanence flux density on operating point under general PM condition of initial 2-D model without overhang effect. $H'_d$ and $B'_d$ represent that of 2-D model which considers overhang effect by increasing remanence flux density. Permeance coefficient would not be changed when remanence flux density is adjusted because permeance coefficient is influenced by shape of magnet, air gap and core. In order to derive calculation formula of the remanence flux density $B'_r$ that considers overhang effect accurately, we make magnetic energy of 2-D model equal to that of 3-D model as follows.

$$B_{OH}H_{OH}V_{OH} = B_d'H_d'V_{no\_OH} \quad (2)$$

$B_{OH}$ and $H_{OH}$ represent the value of coercive force and remanence flux density on operating point of 3-D model with overhang structure. $V_{no\_OH}$ and $V_{OH}$ are magnet volume of 2-D model and 3-D model, respectively. From (1) to (2), calculation formula of remanence flux density $B_r'$ is derived by

$$B_r' = (1 - P_c)\sqrt{\frac{B_{OH}H_{OH}V_{OH}}{P_c V_{no\_OH}}}\,. \quad (3)$$

The bottom dimensions of $V_{OH}$ and $V_{no\_OH}$ are identical but their axial lengths are different. Thus (3) is finally expressed by

$$B_r' = (1 - P_c)\sqrt{\frac{l_{OH}}{l_{no_{OH}}}}\sqrt{\frac{B_{OH}H_{OH}}{P_c}} = (1 - P_c)L_{OH}\sqrt{\frac{B_{OH}H_{OH}}{P_c}} \quad (4)$$

where $l_{no\_OH}$ is axial length of PM of non-overhang model, $l_{OH}$ is that of overhang model and $L_{OH}$ is square root of overhang length ratio. Remanence flux density $B_r'$ that considers overhang effect can be obtained from (4).

## III. Analysis Model

The analysis model is spoke type PM synchronous motor as shown in Fig. 2 and its specifications are represented in Table I. The stack length of rotor and stator core is 20mm. This model has 8mm PM overhang structure now that the axial length of magnet is 28mm. We designed inner frame in order to prevent flux leakage and concentrate flux caused by ferrite PMs which are represented as red and blue parts in Fig. 2.

TABLE I
SPECIFICATIONS OF ANALYSIS MODEL

| Item | Specification |
|---|---|
| Stator Outer Diameter / Inner Diameter (mm) | 272 / 202 |
| Rotor Outer Diameter / Inner Diameter (mm) | 200/120 |
| Number of Poles / Slots | 16 / 24 |
| Stator and Rotor Core Length (mm) | 20 |
| Axial Length of PM (mm) | 28 |
| Air Gap Length (mm) | 1 |
| Remanence of Magnet (T) | 0.41 @ 20 ℃ |

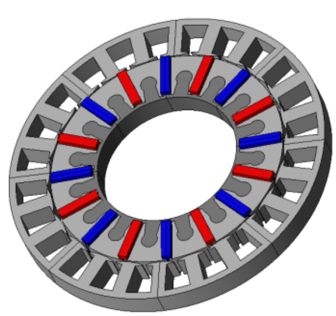
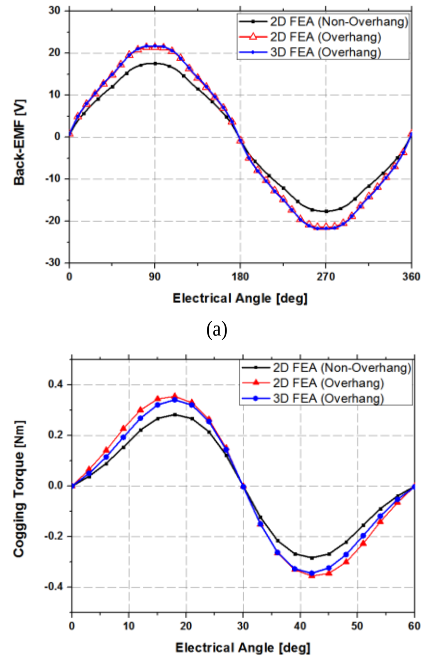


Fig. 2. Analysis model with PM overhang structure.

## IV. Analysis Results

We performed 2-D FEA by using $B_r'$ calculated by (4). 2-D FEA without overhang effect and 3-D FEA on overhang model are also performed. We have compared results of back-electromotive force (EMF) and cogging torque as shown in Fig. 3. Additionally, computation time of 2-D and 3-D FEA is compared as shown in Table I.




(b)

Fig. 3. Comparison of analysis results. (a) Back-EMF. (b) Cogging torque.

TABLE II
COMPUTATION TIME OF NO-LOAD ANALYSIS DURING ONE-PERIOD IN ELECTRICAL ANGLE

| Item | Computation time |
|---|---|
| 2-D Back-EMF analysis | 23 min 41 sec |
| 3-D Back-EMF analysis | 19 hour 17 min 28 sec |

## Conclusion

Previously, overhang parameter has been obtained through variation of PM's operating point. In this paper, we derive calculation formula of reamanence flux density that reflects overhang effect in 2-D FEA through magnetic energy. Proposed method is verified by comparison between results of 2-D FEA with overhang effect and that of 3-D FEA on overhang model.

## V. References

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