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Core Loss Calculation of Permanent Magnet Machines Using Analytical Method

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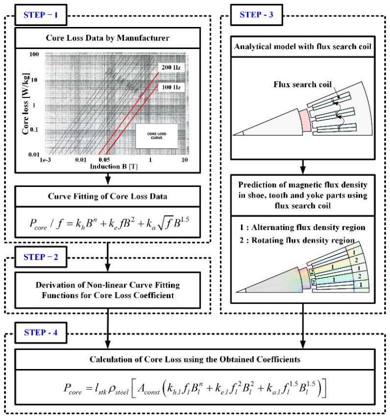
▪Abstract

The core losses are caused by the changing flux densities in various parts of the iron structures in the permanent magnet (PM) machine. Some of these core losses can be significant during high-frequency operations. It is imperative to consider the core losses during the design stage. The purpose of this paper is to analytically predict the core loss of the PM machine at the design stage. The core loss obtained by the analytical method is compared with those obtained using the finite element method and experiments. In order to verify the core loss results obtained using the proposed method, an experimental system was implemented with a commercial PM machine, power analyzer, and the manufactured test PM machine.

▪Process of proposed core loss calculation method



STEP – 1

Core Loss Data by Manufacturer

Curve Fitting of Core Loss Data

$$P_{core}/f = k_h B^n + k_e f B^2 + k_a \sqrt{f} B^{1.5}$$

STEP – 2

Derivation of Non-linear Curve Fitting Functions for Core Loss Coefficient

STEP - 3

Analytical model with flux search coil

Prediction of magnetic flux density in shoe, tooth and yoke parts using flux search coil

1 : Alternating flux density region
2 : Rotating flux density region

STEP - 4

Calculation of Core Loss using the Obtained Coefficients

$$P_{core} = l_{stk}\rho_{steel}\left[A_{const}\left(k_{h,l} f_l B_l^n + k_{e,l} f_l^2 B_l^2 + k_{a,l} f_l^{1.5} B_l^{1.5}\right)\right]$$

FIG. 1. Process of proposed core loss calculation method

- ❖ As shown in Fig. 1, the process followed in the proposed analytical method is given below.
- ❖ - Step-1: rearrangement of the core loss data
- ❖ - Step-2: deduction of the core loss coefficient by curve fitting
- ❖ - Step-3: analytical modeling with a search coil for calculating the flux density.
- ❖ - Step-4: calculation of the core loss using the obtained core loss coefficients and flux density.

- ❖ For core loss modeling, a standard practice is to separate the loss into the following three components: hysteresis (P_h), eddy current (P_e), and anomalous losses (P_a), i.e., the core loss considering the anomalous loss is expressed as follows

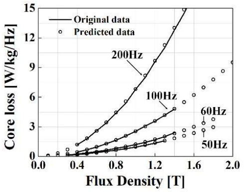


FIG. 2. P_{core}/f vs. B curve and curve fitting for core loss coefficient calculation.

$$\begin{aligned} P_{core} &= P_h + P_e + P_a \\ &= k_h f B^n + k_e f^2 B^2 + k_a f^{1.5} B^{1.5} \end{aligned}$$

- ❖ The function for the frequency of each core loss coefficient can be obtained as follows:

$$\begin{aligned} k_h &= 3.721\cdot\exp(-5f) + 0.005926 \\ k_e &= \exp\left(-0.474\log(f) - 7.002\right) \\ k_a &= \exp\left(-0.002734f - 7.22\right) \\ n &= 1.11f^{0.16} - 0.009f + 0.93 \end{aligned}$$

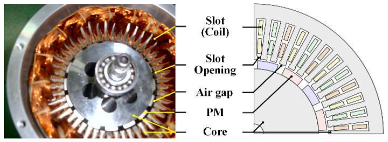


FIG. 3. Permanent magnet machine: prototype and FE analysis model.

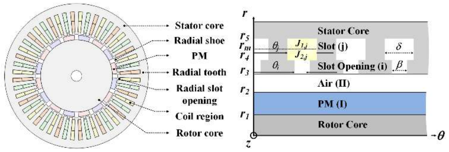


FIG. 4. Simplified analytical model.

- ❖ The magnetic vector potential **A**

$$\mathbf{A}_{\mathbf{zn}}^{\mathbf{I}} = A_0^I + B_0^I \ln r + \sum_{n=1}^{\infty}\left[\left(\begin{matrix} A_n^I r^{-n} + B_n^I r^n \\ + \dfrac{r\mu_0 n}{\left((n)^2-1\right)} M_n \cos n\theta_o \end{matrix}\right)\sin n\theta + \left(\begin{matrix} C_n^I r^{-n} + D_n^I r^n \\ - \dfrac{r\mu_0 n}{\left((n)^2-1\right)} M_n \sin n\theta_o \end{matrix}\right)\cos n\theta\right]\mathbf{i_z}$$

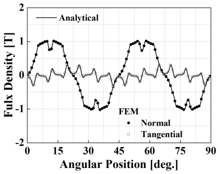
$$\mathbf{A}_{\mathbf{zn}}^{\mathbf{II}} = A_0^{II} + B_0^{II}\ln r + \sum_{n=1}^{\infty}\left[\left(A_n^{II} r^{-n} + B_n^{II} r^n\right)\sin n\theta + \left(C_n^{II} r^{-n} + D_n^{II} r^n\right)\cos n\theta\right]\mathbf{i_z}$$

$$\mathbf{A}_{\mathbf{zk}}^{\mathbf{i}} = A_o^i + B_o^i \ln r + \sum_{k=1}^{\infty}\left(A_k^i r^{-\frac{k\pi}{\beta}} + B_k^i r^{\frac{k\pi}{\beta}}\right)\cos\left(\frac{k\pi}{\beta}\left(\theta - \theta_i\right)\right)\mathbf{i_z}$$

$$\mathbf{A}_{\mathbf{zm}}^{\mathbf{j}} = A_o^j + B_o^j \ln r - \frac{1}{4}\mu_o J_{j0} r^2 + \sum_{m=1}^{\infty}\left(A_m^j r^{-\frac{m\pi}{\delta}} + B_m^j r^{\frac{m\pi}{\delta}} + \frac{\mu_o J_{j,m} r^2}{\left(\dfrac{m\pi}{\delta}\right)^2 - 4}\right)\cos\left(\frac{m\pi}{\delta}\left(\theta - \theta_j\right)\right)\mathbf{i_z}$$

▪ Core loss calculation

- ❖ From ∇ × **A** = **B**, the normal and the tangential component of the flux density can be expressed as

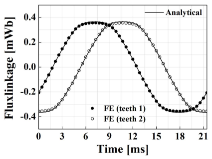


$$\mathbf{B_r} = \frac{1}{r}\frac{\partial \mathbf{A}}{\partial \theta}\mathbf{i_r}$$

$$\mathbf{B_\theta} = -\frac{\partial \mathbf{A}}{\partial r}\mathbf{i_\theta}$$

Fig. 5. Flux density produced by PMs at the center of air gap.

- ❖ For slotted structures, the computation of the flux linkage using a method based on the winding function theory is not suitable. Instead, a method based on the Stokes theorem using a vector potential in the stator slot is used. We first deter-mine the flux over each slot *j* having a cross section A_{slot} at a given rotor position θ_0. We assumed that the current is uniformly distributed over the slot coil area; thus, the vector potential can be averaged over the slot coil area to represent the coil.



$$\phi_t = \frac{l_{stk}}{A_{slot}}\int_{r_m}^{r_2}\int_{\theta_i+\frac{1}{2}(\beta-\delta)}^{\theta_i+\frac{1}{2}(\beta+\delta)} A_{zm}^j \, r dr d\theta$$

$$\phi_b = \frac{l_{stk}}{A_{slot}}\int_{r_1}^{r_m}\int_{\theta_i+\frac{1}{2}(\beta-\delta)}^{\theta_i+\frac{1}{2}(\beta+\delta)} A_{zm}^j \, r dr d\theta$$

$$\left(\lambda_{t,1} \; \cdots \; \lambda_{t,Q}\right) = \left[C_l\right]\left[\phi_{t,1} \; \cdots \; \phi_{t,Q}\right]'$$

$$\left(\lambda_{b,1} \; \cdots \; \lambda_{b,Q}\right) = \left[C_r\right]\left[\phi_{b,1} \; \cdots \; \phi_{b,Q}\right]'$$

Fig. 6. Flux linkage produced by PMs at the stator teeth.

- ❖ [C_l] and [*Cr*] are the transpose of the connecting matrix that represents the stator windings for searching flux linkage in the stator core.

TABLE I
SPECIFICATIONS OF THE PROTOTYPE PM MACHINE

Parameters	Values	Parameters	Values
r_1 (inner radius of rotor)	40 mm	Slot-opening	2 mm
r_2 (outer radius of PMs)	45 mm	Number of poles	16
r_3 (inner radius of stator)	46 mm	Number of slots	48
r_4 (bottom radius of slots)	48.5 mm	Pole arc ratio	0.74
r_5 (top radius of slots)	71 mm	Core material	35PN250
l_{stk}(active length of motor)	68 mm	Grade of PM	N35SH

- ❖ Core loss considering the rotating and alternating magnetic fields can be calculated by

$$P_{core} = l_{stk}\rho_{steel}\left[A_{const}\left(k_{h.}f\,B_m^n + k_e f^2 B_m^2 + k_a f^{1.5} B_m^{1.5}\right)\right]$$

- ❖ B_m is the maximum flux density. A_{const} represent the alternating and the rotating field areas judged from the loci of the time harmonic in previous studies. ρ_{steel} is steel's specific gravity. l_{stk} is the effective axial length of the PM machine.

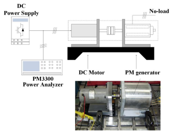


Fig. 7. Experimental setup for measurement core loss.

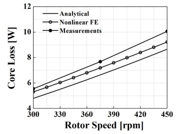


Fig. 8. Comparison of analytical predictions with FE and experimental results.

- ❖ In order to verify the core loss results predicted by curve fit-ting method and magnetic behavior analysis, the experimental system has been implemented with commercial DC motor, power analyzer (PM3300-Voltech) and manufactured test motor.

- ❖ For the case when the PM machine is driven at rated speed 450 rpm, the analytical predictions, FE analysis and measurements for the core loss has a result of 8.64 W, 9.2 W and 10.26 W, respectively.

▪Conclusion

- ❖ In this paper, an analytical method for computing the core loss in PM machine was presented.
- ❖ The stator core loss can be calculated from the loss factor calculated by curve fitting of the original core loss data and the magnetic flux density of the stator calculated by the analytical method.
- ❖ At this time, the behavior of the magnetic field was referred to the existing study.
- ❖ In order to have a good precision in the analytical results, the number of harmonic terms used in the computations was equal to N=70 (air-gap and PM subdomains) and M=K=15 (slots and slot-opening subdomains).
- ❖ For a given rotor position, the computation time is approximately 10 s with the analytical model, whereas the nonlinear FE analysis takes approximately 1020 s for a mesh of 26510 elements.
- ❖ The analytical method presented in this paper is very convenient for comprehensive studies and incorporation into optimization.