

# Calculation of Electromagnetic Losses in Arc Motors Based on the Subdomain Method

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The arc linear flux switching permanent magnet motor (AL FSPM) is suitable for large-scale scanning equipment and robotic joints, featuring flexible installation, high positioning accuracy, and low torque ripple. Additionally, compared to traditional rotor permanent magnet (PM) arc line motors, it solves the issues of exposed PM and low utilization. Although the subdomain method offers high computational accuracy in analyzing magnetic fields, it has not yet been applied to the magnetic field analysis of AL FSPM. This paper proposes a subdomain model for the magnetic field of AL FSPM, solving for the motor vector magnetic potential distribution at different rotor positions, and subsequently calculating the magnetic field distribution of the motor's transient field. Ultimately, key electromagnetic parameters such as air gap flux density, winding flux linkage, inductance, and losses are determined. This method can effectively shorten the computation time while ensuring accuracy, laying the foundation for the optimization of AL FSPM.

**Index Terms**—stator permanent magnet arc motor, subdomain method, magnetic field analysis have been calculated.

## I. INTRODUCTION

The subdomain method is often used in the magnetic analysis of ordinary PM motors [1-3]. However, the AL FSPM includes circumferential arc end regions, and its structure is relatively complex. There has been no literature report on the electromagnetic calculation method based on the subdomain model for the AL FSPM.

This article takes an AL FSPM as an example, carries out subdomain division, calculates the vector magnetic potential in each area, and obtains the magnetic flux density distribution within the motor. Then it solves for the motor's inductance, electromagnetic torque, and electromagnetic losses. The validity of the model in this article is verified through finite element analysis.

## II. AL FSPM STRUCTURE

### A. The Subdomain Method for Establishing AL FSPM

The solution domain division for a single stator in AL FSPM is shown in Fig. 1. where the rotor slot is domain I, the air gap is solution domain II, the stator PM is domain III, the stator slot is domain IV, the external air domain is domain V, and the arc-shaped end is solution domain VI. In domains I, II, V, and VI, the Laplace equation is satisfied.

$$\nabla^2 A = \frac{\partial^2 A}{\partial r^2} + \frac{1}{r} \frac{\partial A}{\partial r} + \frac{1}{r^2} \frac{\partial^2 A}{\partial \theta^2} = 0 \quad (1)$$

In solving for domain III, IV, satisfying the Poisson equation.

$$\nabla^2 A = \begin{cases} -\mu_0 \frac{M_\theta}{r} & \text{solution domain III} \\ -\mu_0 J & \text{solution domain IV} \end{cases} \quad (2)$$

By establishing continuous boundary conditions between domains I to VI, the vector magnetic potential A and magnetic flux density B in each region can be solved.

Thus, the key electromagnetic parameters of the motor, including the winding flux linkage, inductance, and losses,

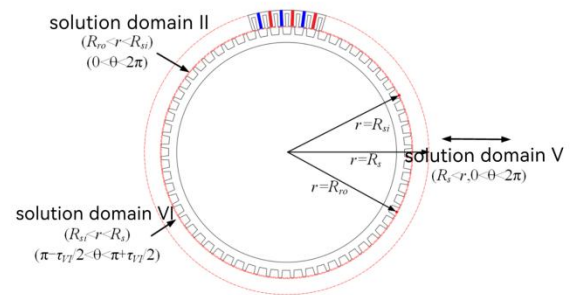


Fig.1 AL FSPM Subdomain Division

### B. Solution of Air Gap Flux Density and Flux Linkage

The vector magnetic potential distribution in the domain II has been determined, and thus the formula for calculating the air gap magnetic flux density is obtained as follows

$$B_{II,r}(r,\theta) = \frac{1}{r} \frac{\partial A_{II}(r,\theta)}{\partial \theta} = -\frac{n_{II}}{r} \sum_{n_{II}=1}^{\infty} \left[ a_n^{II} \left( \frac{r}{R_{ro}} \right)^{n_{II}} + b_n^{II} \left( \frac{r}{R_{si}} \right)^{-n_{II}} \right] \sin(n_{II}\theta) + \frac{n_{II}}{r} \sum_{n_{II}=1}^{\infty} \left[ c_n^{II} \left( \frac{r}{R_{ro}} \right)^{n_{II}} + d_n^{II} \left( \frac{r}{R_{si}} \right)^{-n_{II}} \right] \cos(n_{II}\theta) \quad (3)$$

Where  $B_{II,r}$  is the radial component of magnetic flux density,  $B_{II,\theta}$  is the Circumferential component of magnetic flux density.

By Stokes theorem, then the flux linkage of the  $k$ -th stator coil is

$$\psi_k = \frac{N_c I_a}{S_{ss}} \left( \int_{\theta_{k+1}-\frac{\tau_{ss}}{2}}^{\theta_{k+1}+\frac{\tau_{ss}}{2}} \int_{R_{si}}^{R_{sb}} A_{II,k}(r, \theta; \theta) dr - \int_{\theta_k-\frac{\tau_{ss}}{2}}^{\theta_k+\frac{\tau_{ss}}{2}} \int_{R_{si}}^{R_{sb}} A_{II,k}(r, \theta; \theta) dr \right) \quad (4)$$

Where  $I_a$  is the axial length of the motor,  $N_c$  is the number of turns of the coil,  $S_{ss}$  is the slot area of motor stator.

Taking a single arc-shaped stator with an A-B-C winding sequence as an example, the flux linkage of the three-phase winding is

$$\begin{bmatrix} \psi_A \\ \psi_B \\ \psi_C \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \psi_{k=1} \\ \dots \\ \psi_{k=6} \end{bmatrix} \quad (5)$$

Ultimately, the flux of the three-phase windings in the AL FSPM is the superposition of the fluxes from all same-phase windings across all arc-shaped stators.

### C. Solution for Terminal Voltage and Inductance

When the rotor turns over a pole pitch  $\tau_r$ , AL FSPM experiences an electrical cycle, and  $n_a$  rotor position points are calculated at equal steps within a  $\tau_r$ , then the instantaneous expression of the phase voltage under load is

$$U_{EMF} = \frac{\Delta\psi}{\Delta t} R_i \quad (6)$$

$$\Delta t = \frac{2\pi}{\omega N_r n_a} \quad (7)$$

Where  $U_{EMF}$  is the Phase voltage,  $\Delta\psi$  is the difference in flux linkage between two adjacent calculation points in a single-phase winding,  $\omega$  is motor speed.

Taking phase A winding as an example.

$$L_a = \frac{\Delta\psi_A}{\Delta I_A}, \quad L_{ab} = \frac{\Delta\psi_B}{\Delta I_A}, \quad L_{ac} = \frac{\Delta\psi_C}{\Delta I_A} \quad (8)$$

Where  $\Delta I_A$  is the Increment of phase current in phase A winding,  $\Delta\psi_A$  is the Increment of magnetic flux in phase A winding caused by  $\Delta I_A$ ,  $\Delta\psi_B$  is the Increment of magnetic flux in phase B winding caused by  $\Delta I_A$ ,  $\Delta\psi_C$  is the Increment of magnetic flux in phase C winding caused by  $\Delta I_A$ .

### III. SUBDOMAIN METHOD FOR SOLVING LOSSES

The calculation methods for the various electromagnetic losses in the AL FSPM are as follows.

(1) The prototype has a low rotational speed, resulting in smaller eddy currents and eddy current losses in the wire. Therefore, the armature winding loss is only considered to be the resistive loss.

(2) Since the vector magnetic potential  $A_{III}$  of the permanent magnet is known, the eddy current in the  $j$  block can be determined using the adjacent two calculation points of the subdomain model.

$$J_{e,j} = -\sigma_{PM} \frac{\Delta A_{III}}{\Delta t} + C(t) \quad (9)$$

There is an insulated fixing adhesive between the gap of the PM and the stator core, and there is no interaction of eddy currents between them, then  $C(t)$  in the formula is a variable that keeps the total eddy current in a single PM at 0, and it has

$$C(t) = \frac{2}{\tau_{PM}(R_s^2 - R_{st}^2)} \int_{\theta_j - \frac{\tau_{PM}}{2}}^{\theta_j + \frac{\tau_{PM}}{2}} \int_{R_{st}}^{R_s} \sigma_{PM} \frac{\Delta A_{III}}{\Delta t} r dr d\theta \quad (10)$$

The average eddy current loss in a PM over one electrical cycle is

$$P_{PM} = \frac{l_a \omega}{\tau_r \sigma_{PM} n_a (N_s - 1)} \sum_{n=1}^{n_a} \sum_{j=1}^{N_s-1} \int_0^{\tau_r} \int_{R_{st}}^{R_s} \int_{\theta_j - \frac{\tau_{PM}}{2}}^{\theta_j + \frac{\tau_{PM}}{2}} J_{e,j}^2 r dr d\theta dt \quad (11)$$

(3) Bertotti model divides the iron loss  $P_{Fe}$  into three parts. Since the subdomain model only solves for the magnetic potential in the non-core regions, the key to calculating iron loss in the core regions lies in analyzing the magnetic flux

density  $B$  in these regions. This analysis is based on the distribution characteristics of the AL-FSPM magnetic field and the results from the non-core regions.

$$P_{Fe} = k_h f B^2 + k_e f^2 B^2 + k_a f^{1.5} B^{1.5} \quad (12)$$

Where  $k_h$ ,  $k_e$ ,  $k_a$  are the loss coefficients for hysteresis, eddy current, and additional losses, respectively. Generally,  $k_a$  is more than two orders of magnitude smaller than  $k_e$ , and the additional loss can be ignored in analysis.

The direction of magnetic density in the rotor teeth is radial, and the average magnetic density  $B_{rt,i}$  of the  $i$ -th rotor tooth is calculated from the vector magnetic potentials of the  $i$  th and  $(i+1)$  th rotor slots on both sides

$$B_{rt,i} = \frac{1}{\tau_{rt} R_{ro} S_{rs}} \left\{ \int_{\theta_i - \frac{\tau_{rs}}{2}}^{\theta_i + \frac{\tau_{rs}}{2}} \int_{R_{rb}}^{R_{ro}} A_{I,i}(r, \theta) dr d\theta - \int_{\theta_{i+1} - \frac{\tau_{rs}}{2}}^{\theta_{i+1} + \frac{\tau_{rs}}{2}} \int_{R_{rb}}^{R_{ro}} A_{I,i+1}(r, \theta) dr d\theta \right\} \quad (13)$$

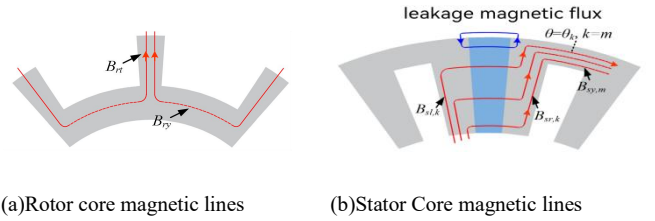


Fig.2 Magnetic flux path of the stator and rotor core

The eddy current losses in the PM calculated by the finite element method and the subdomain model are 5.58 W and 5.88 W, respectively, with an error of 5.38%; the rotor iron losses are 1.65 W and 1.68 W, respectively, with an error of 1.82%; the stator iron losses are 2.28 W and 2.09 W, respectively, with an error of 8.33%.

### IV. CONCLUSION

This article establishes the spatial distribution of the vector magnetic potential of each subdomain by modeling and analyzing the AL FSPM using the subdomain method. ensuring accuracy while reducing computation time. Finally, the loss comparison of the rotor, stator, and PM is verified through the finite element method, and the relevant differences are analyzed. Ultimately, it demonstrates the speed and effectiveness of the subdomain method for analyzing AL FSPM and solving electromagnetic parameters.

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