Autonomous High-Fidelity Design and Multiphysics Modeling of Axial Flux Permanent Magnet Motors

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***Abstract*—This paper presents a deterministic analytical framework for the high-fidelity design of Axial Flux Permanent Magnet (AFPM) motors. The methodology integrates seven discrete physical domains into a unified optimization environment, replacing conventional static approximations with dynamic, non-linear governing equations derived directly from operational physics.**

I. The Seven-Module Analytical Framework

The proposed high-fidelity model is structured into seven discrete modules, each addressing a critical physical phenomenon observed in AFPM topologies.

A. Module 1: Fringing and Leakage Flux

To compensate for the decrease in permeance due to stator slotting, the effective air-gap (g_{eff}) is modeled via Carter's coefficient k_c and the analytical fringing factor γ:

$$\begin{aligned} g_{\text{eff}} &= g \cdot \frac{\tau_s}{\tau_s - \gamma g} \\ \gamma &= \frac{4}{\pi}\left[\frac{w_s}{2g}\tan^{-1}\left(\frac{w_s}{2g}\right) - \ln\sqrt{1+\left(\frac{w_s}{2g}\right)^2}\right] \end{aligned} \tag{1}$$

B. Module 2: AC Copper Losses (Skin and Proximity)

Frequency-dependent resistance escalation is governed by Dowell's analytical equation, accounting for the interaction between conductor layers:

$$k_{\text{ac}} = \xi\left[\frac{\sinh 2\xi + \sin 2\xi}{\cosh 2\xi - \cos 2\xi} + \frac{2(m^2-1)}{3}\frac{\sinh\xi - \sin\xi}{\cosh\xi + \cos\xi}\right] \tag{2}$$

C. Module 3: Non-linear Magnetic Saturation

The ferromagnetic saturation in M-19 steel is represented through a high-order power-law fit of the B-H curve to monitor the Saturation Factor (K_{sat}):

$$H(B) = 14.6B + 31.4B^9 \tag{3}$$

D. Module 4: Aerodynamic and Mechanical Losses

Windage losses are calculated using the moment coefficient (C_m) derived from the Reynolds number of the rotating disc:

$$P_{\text{windage}} = 0.5C_m\rho\omega^3R^5 \tag{4}$$

E. Module 5: Magnet Eddy Current Losses

Losses within the NdFeB magnets are modeled based on slot-passing frequencies (ω_{slot}) and flux ripple amplitudes (β):

$$P_{\text{eddy}} = \frac{1}{12}\sigma_{\text{mag}}\omega_{\text{slot}}^2B_{\text{ripple}}^2w_{\text{mag}}^2V_{\text{mag}} \tag{5}$$

F. Module 6: Axial Pull and Rotor Deflection

The Maxwell Stress Tensor is employed to predict the axial force (F_{ax}), coupled with plate theory for maximum deflection ($\delta_{\max}$) calculation:

$$\begin{aligned} F_{\text{ax}} &= \frac{B_{\text{gap}}^2A_{\text{active}}}{2\mu_0} \\ \delta_{\max} &= \frac{qR^4}{64D}\left[1-\left(\frac{r_i}{R}\right)^2\right]^2 \end{aligned} \tag{6}$$

G. Module 7: Cogging Torque and NVH

Vibrational harmonics are minimized by optimizing the ratio between poles (P) and slots (S) to reduce peak-to-peak cogging torque:

$$T_{\text{cog}} \propto \frac{B_{\text{gap}}^2A_{\text{active}}g_{\text{eff}}}{2\mu_0}\cdot e^{-0.1\frac{\text{LCM}(P,S)}{P}} \tag{7}$$

II. Conclusion

The integration of these seven modules provides a robust pre-design validation stage. By constraining the optimization through these physical limits, the final design ensures electromagnetic optimality and mechanical stability.