

Neural Network-Based Estimation of Electromagnetic Forces and Vibration Reduction in EV Propulsion Motors

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Electric vehicle (EV) propulsion motors operate under different conditions, causing input currents to vary based on MTPA and MTPV control criteria. These changes in input currents result in non-linear variations in air-gap electromagnetic force harmonics (AEFHs). To reduce vibrations across various operating points, non-linear characteristics must be considered during the design stage. However, designing to reduce AEFHs early in the design stage across various operating points incurs high computational costs, as it requires d-q flux linkage information for various d-q current combinations to determine input conditions and calculate AEFHs based on control logic. To address this, we employ a neural network (NN) model to predict d-q flux linkages and AEFHs based on geometric parameters and d-q currents. The trained NN uses currents derived from MTPA and MTPV control logic along with voltage equations based on the predicted d-q flux linkages. This enables the prediction of motor performance and AEFHs across various operating conditions, facilitating computationally efficient motor design.

Index Terms—Air-gap flux density, electromagnetic forces, electromagnetic-induced vibration, neural network.

I. INTRODUCTION

THE interior permanent magnet synchronous motor (IPMSM) is a key component in electric vehicles (EVs). Its remarkable performance stems from the use of permanent magnets and the capability to sustain high power output at elevated speeds. With growing consumer demand for refinement and convenience in vehicles, the focus on vibration characteristics in EVs has grown significantly. Vibration in propulsion motors arises from a combination of electromagnetic, mechanical, and electrical factors. Among these, electromagnetic factors are particularly significant [1] - [5]. They involve the generation of radial air-gap electromagnetic forces (AEFs) caused by the interaction between the armature and the permanent magnet field. These forces act as two-dimensional harmonic excitation, both temporally and spatially, causing deformations that lead to stator vibrations[4]. Numerous studies have aimed to minimize air-gap electromagnetic force harmonics (AEFHs) to enhance motor vibration characteristics, contributing to the overall refinement of EV propulsion systems.

The first approach involves improving vibration characteristics through the design parameters. S. Zhu et al. [2] found that the 14-pole 12-slot model reduced vibrations caused by the 2nd harmonic of AEFs compared to the 10-pole 12-slot model. Additionally, incorporating q-axis notches and optimizing rotor shape reduced air-gap flux density harmonics by 12dB [3]. The second approach includes a method to reduce the computational cost of vibration analysis and vibration reduction design has been proposed. In [1], they proposed an optimization process to minimize vibrations induced by AEFHs. Using the analytical equation of stator, the vibrations were predicted, and an optimization algorithm explored the design space. However, the methods proposed in these studies primarily focus on reducing vibrations at a single operating point, which may limit their effectiveness for propulsion motors

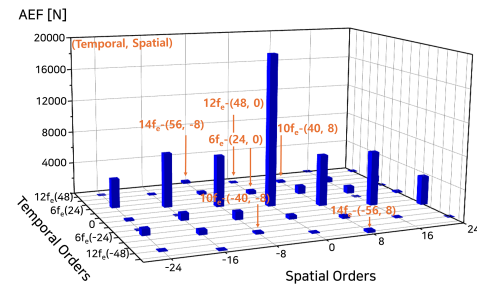


Fig. 1. The spectrum of AEFHs of a single point after 2D-FFT for 8-poles and 48-slots EV propulsion motor.

operating under variable conditions. Furthermore, during the design stage, considering a wide range of driving scenarios requires accounting for electromagnetic characteristics that vary with motor geometry. This involves first calculating flux linkages for various d-q current combinations, then obtaining input current information based on control logic, which significantly increases the computational effort needed to calculate AEFHs.

Therefore, this study proposes a method to reduce electromagnetic computational costs by constructing a trained neural network for flux linkages and AEFHs based on design parameters and input currents. Furthermore, this approach enables the design of EV propulsion motors that account for vibrations across various operating points with reduced computational costs.

II. CALCULATION OF AEFHs BASED ON D-Q CURRENT COMBINATIONS

The AEFs were derived using electromagnetic FEA, and the results obtained through 2D-FFT are presented in Fig. 1. The primary AEFHs that significantly induce vibration are not

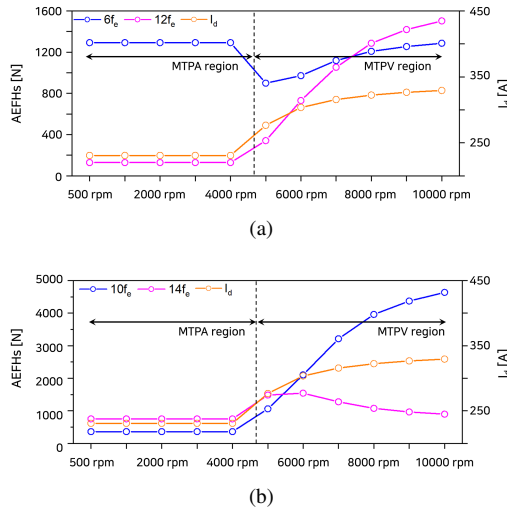


Fig. 2. The characteristics of AEFHs according to different operating points (a) $6f_e$, $12f_e$ and (b) $10f_e$, $14f_e$.

those with the largest forces, but rather those with relatively smaller forces, such as $6f_e$ and $12f_e$ in the target system. This is because the eigenfrequency, as the solution of the homogeneous mechanical governing equation of the stator, shows that the displacement caused by the zeroth spatial order of AEF has the most significant impact [4] - [6]. It should be noted that $2f_e$ represents the AEF with a temporal $2p$ -th order (where p denotes the pole pair), corresponding to twice the fundamental frequency. Additionally, AEFHs with frequencies close to the natural frequency, such as $10f_e$ and $14f_e$, can also cause significant displacement, requiring careful consideration [5]. Fig. 2 illustrates the non-linear variations of AEFHs at the maximum power conditions of the motor under the MTPA and MTPV control criteria. $6f_e$ represents the largest force under the MTPA criterion, slightly decreases, and then increases again as the magnitude of the d-axis current rises under the MTPV criterion. Meanwhile, $12f_e$ and $10f_e$ exhibit minimum values under the MTPA criterion, but they worsen as the magnitude of the d-axis current increases in the MTPV operating region. In contrast, $14f_e$ represents a force that initially increases in the MTPV region but then decreases.

III. ESTIMATION OF AEFHS BASED ON NEURAL NETWORK

Section II examined the non-linear characteristics of AEFs under various operating points. Predicting AEFHs based on motor geometry and input currents during the design stage is impractical due to the high computational costs of considering all conditions. Therefore, a neural network (NN)-based approach is proposed to enable rapid evaluation of motor performance and AEFHs during the design stage. The NN model was trained on a dataset constructed with input currents and geometric parameters as independent variables, and d-q flux linkages and AEFHs ($6f_e$, $12f_e$, $10f_e$ and $14f_e$) as dependent variables. The d-q flux linkages are used to build a model that considers various operating points and torque levels based on the governing equations in the d-q reference frame. The AEFHs serve as training data for calculating values

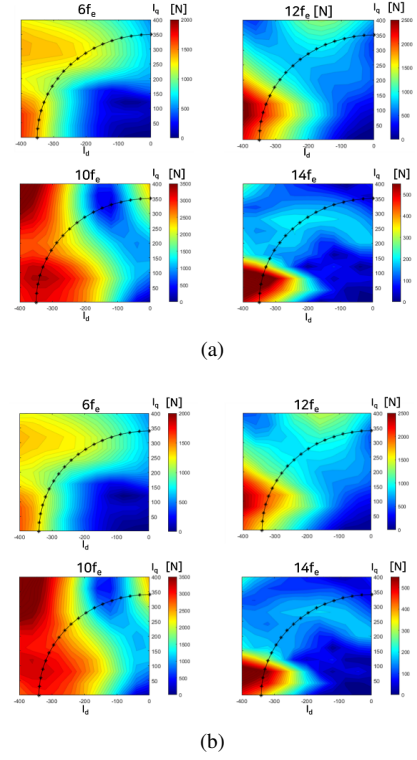


Fig. 3. The result of AEFHs map according to the d-q currents (a) FEA and (b) predicted by trained NN.

at different operating points. Fig. 3 presents the AEFHs map, with (a) showing the FEA results and (b) presenting the map constructed using the trained NN model based on d-q currents, both demonstrating consistency.

In the manuscript, we detail the regression performance and processes of the trained NN. We also demonstrate a method to reduce computational costs in the design stage by accounting for both motor performance and AEFHs. Finally, we present experimental results that validate motor vibrations based on estimated AEFHs.

REFERENCES

- [1] L. Yao, J. -X. Shen, Y. Wang and D. Shi, "Fast Prediction and Staged Optimization of Electromagnetic Vibration in Permanent Magnet Synchronous Motor," in *IEEE Trans. Ind. Electron.*, vol. 71, no. 1, pp. 115-125, Jan. 2024, doi: 10.1109/TIE.2023.3250755.
- [2] S. Zhu, W. Zhao, J. Ji, G. Liu and C. H. T. Lee, "Design to Reduce Modulated Vibration in Fractional-Slot Concentrated-Windings PM Machines Considering Slot-Pole Combination," in *IEEE Trans. Transp. Electr.*, vol. 9, no. 1, pp. 575-585, March 2023, doi: 10.1109/TTE.2022.3192639.
- [3] A. K. Putri, S. Rick, D. Franck and K. Hameyer, "Application of Sinusoidal Field Pole in a Permanent-Magnet Synchronous Machine to Improve the NVH Behavior Considering the MTPA and MTPV Operation Area," in *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2280-2288, May-June 2016, doi: 10.1109/TIA.2016.2532289.
- [4] Gieras, Jacek F., Chong Wang, and Joseph Cho Lai. *Noise of polyphase electric motors*. CRC press, 2018.
- [5] N. -H. Kim, J. -H. Cho, J. H. Lee, H. -K. Yeo, S. -W. Jung and S. -Y. Jung, "Mitigation and Investigation of NVH Characteristics of Multi-Inverter System on EV Propulsion Motor," 2024 IEEE Transportation Electrification Conference and Expo (ITEC), Chicago, IL, USA, 2024, pp. 1-5, doi: 10.1109/ITEC60657.2024.10599057.
- [6] N. -H. Kim, J. -H. Cho, J. H. Lee and S. -Y. Jung, "Analysis of Vibration Characteristics Considering the Modulation Effect According to Rotor Bars of Induction Motor for EVs," *J. Electr. Eng. Technol.* (2024). <https://doi.org/10.1007/s42835-024-02031-2>