Research on Cogging Torque Calculation for Interior Permanent Magnet Machine based on Lumped-Circuit Parameters

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Abstract—This paper is the first research showing that it is possible and effective to predict cogging torque waveform of interior permanent machine (IPM) using only analytical model. Based on proposed virtual permanent magnet concept, interior permanent magnet can be considered as surface permanent magnet having zero height and unit relative permeability, and then it is used for calculating the cogging torque with conventional techniques. The proposed method is validated by finite element analysis (FEA).

Index Terms—Analytical model, cogging torque, interior permanent magnet machine.

I. INTRODUCTION

Cogging torque is defined as a torque produced by magnetic forces between stator teeth and the magnets of rotor, and it can be an important performance index of acoustic noise and vibration. Thus, it is generally desirable to reduce the cogging torque at design stage.

Regarding analysis models for the torque, there are several techniques for surface permanent magnet machine (SPM) based on analytical approaches which is useful and practical in terms of their calculating time compared to FEA. In the case of IPM, however, it is difficult to take magnetic saturation and complex rotor structure into account in space harmonic analysis method[1]. Thus, numerical approach such as FEA has been inevitably used, which should be very time consuming [1]-[3].

In this paper, a simple analytical technique based on both lumped-circuit and existing cogging torque model, is proposed to synthesize the cogging torque waveform in IPM.

II. ANALYSIS MODEL AND LUMPED MAGNETIC CIRCUIT

Fig. 1 shows the IPM machine with 'V' shape permanent magnet (PM) having internal and external bridges.

The lumped models for open-circuit field is shown in Fig. 2. \( \alpha_s \) is the pole-arc to pole-pitch ratio and \( N_p \) is the number of magnet poles. \( R_{sb1} \) and \( R_{sb2} \) are the reluctances of internal and external bridges and the corresponding flux are \( \phi_{sb1} \) and \( \phi_{sb2} \) which are represented by flux line as shown in Fig. 1.

\( \phi_s \) and \( \phi_{leak} \) are the flux source and the leakage flux of PM. \( \phi_{int} \) and \( \phi_{2int} \) are the magnet end-leakage fluxes and the corresponding reluctances are \( R_{int} \) and \( R_{2int} \). \( R_s \) and \( R_r \) are the reluctances of the stator yoke and rotor yoke. Detail expression for the lumped parameters can be found in [4].
III. PROPOSED COGGING TORQUE CALCULATION METHOD

In order to combine lumped-circuit model with the conventional cogging torque techniques which consider only radial flux density waveform, a new virtual PM (VPM) concept is proposed. The illustration of the idea is represented in Fig. 3.

With respect to radial flux density distribution, the pattern of SPM and IPM having 1-layer magnet are similar. Thus, we can regard the IPM structure as SPM having zero height and unit relative permeability of PM while it still has same radial flux density and the ratio of pole-arc to pole pitch of IPM. Therefore, it is possible to predict the cogging torque of IPM with existing cogging torque models used for SPM.

It is worth noting that this concept is only available for radial air-gap flux density. In addition, it is not necessary to calculate equivalent residual-flux density ($B_r$) of the VPM because operating point of the magnet was already considered in lumped-circuit model. Indeed, the cogging torque calculation model used in this report do not utilize the $B_r$ but use only flux density of air-gap predicted by lumped-circuit model. Some of techniques, two models for the concept are selected.

A. Model I

The cogging torque can be calculated analytically from the net lateral force acting on the stator teeth[3]:

$$T_{cog} (\alpha) = \frac{L_{ef}}{2\mu_0} \left[ \frac{r_1}{0} \left( B(\alpha) \lambda_1 \right)^2 \left( R_x + r_1(\alpha) \right) d\alpha \right]$$

where $B(\alpha)$ is gained from the lumped-circuit parameters. Thanks to the virtual PM, the permeance and the relative permeance for the flux of PM in the slot can be simplified into

$$\lambda = \frac{\mu_0}{g + \frac{2\pi r_i}{4} \frac{h_m}{\mu_r}} \lambda, \quad \frac{\lambda}{\mu_0} = \frac{\lambda}{\mu_0} = \frac{\lambda}{g}$$

The illustration of Model I is represented in Fig. 4.

B. Model II

By supposing that energy variation in PMs and iron is negligible compared to that of air-gap, the cogging torque can be expressed as follow[5]:

$$T_{cog} (\alpha) = \frac{\partial W_{airgap} (\alpha)}{\partial \alpha} = \frac{\partial}{\partial \alpha} \left[ G^2(\theta)B^2(\theta, \alpha) dV \right]$$

where $G(\theta)$ is a modulation function called air-gap relative permeance.

IV. SIMULATION RESULTS AND DISCUSSION

Fig. 5 shows comparison results of air-gap flux density waveform by the lumped-circuit and FEA. Based on (1), (2) and (3), the cogging torque waveform of IPM can be predicted and their results are shown in Fig. 6. In order to confirm the performance of Model I and Model II in reducing cogging torque of IPM, influence of pole-arc to pole pitch ratio was investigated as shown in Fig. 7. From the analysis results, it is shown that Model I shows better performance results compared to Model II. Moreover, Model I can find optimal point for minimum cogging torque as shown in Fig. 7.

REFERENCES