Influence of Rotor Structure and Number of Phases on First and Second Order Characteristics of TOYOTA PRIUS Electrical Machine Type

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Introduction

This paper investigates the influence of the rotor structure, more specifically, the influence of the open angle between the two magnet's segments of each V-shape pole on the general characteristics of the machine keeping always the same magnets volume. In fact the investigation is done by using a free Finite Elements Methods (FEM) program coupled with another optimization program. This obtained methodology is used to analyze a wide range of first and second order phenomena like the average and oscillation of torque, cogging torque, torque-speed characteristics.

I. Studied PRIUS Machine

A. The average torque $T_{average}$ (first order characteristic)

We have calculated using FEM program "femm" the average torque of the machine according to the electrical angle ψ_e (angle between current and back-EMF vector), for different values of the magnet open angle α without changing the shape of the magnet, see figure 1, h is the distance between the middle point of each magnet pole and the outer circumference of the rotor.

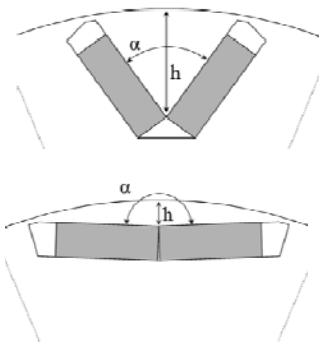

Figure 1. Permanent magnet configurations.

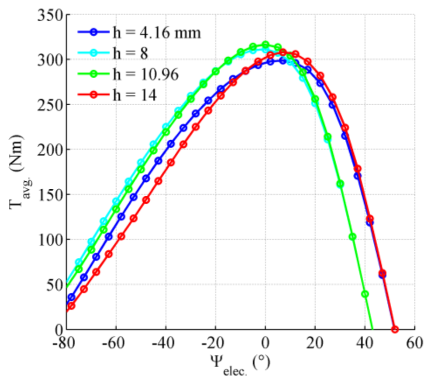

Figure 2. Average torque versus electrical phase.

The results are shown in figure 2. It is clear that the average electromagnetic torque ($\psi_e = 0$) does not vary so much with the value of magnet open angle. On the other hand for another ψ_e value ($\psi_e = \pm 20°$) the curves of average torque which correspond to different α are getting far from each other. The raison is the reluctant torque which is likely more affected by α than electromagnetic one, because of changing in inductances values L_d, L_q.

B. The cogging torque (second order characteristic)

This study also investigates the effects of magnet's open angle on the second order phenomena of PRIUS machine. A methodology consists of coupling between an optimization program of Matlab and the FEM "femm" is applied to find the optimal magnet's open angle $\alpha_{optimal}$ which produces the minimum cogging torque possible [1]. The criteria chosen for this optimization was minimizing the RMS value of cogging torque. The result of optimization was $h_{optimal} = 11.515\ mm$ while the original value of PRIUS machine is $h = 10.96\ mm$. Figure 3 shows the cogging torque for different magnet's open angles.

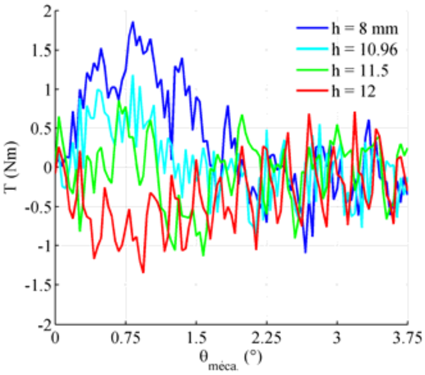

Figure 3. Cogging torque.

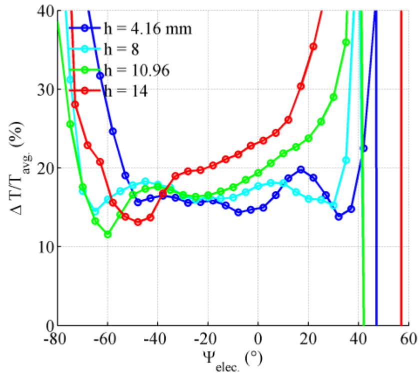

Figure 4. Relative torque ripple.

C. Torque ripple, Back-EMF harmonics, and flux distortion (second order characteristics)

Continuing our study of the second order phenomena, the torque ripple is the second to be examined, by searching how the curve of torque oscillation amplitude according to electrical angle ψ_e changes with different magnet's open angle. In order to have comparable curves, relative amplitude of oscillation is considered $\Delta T/T_{average}(\psi_e, \alpha)$.

The result is an increase in the oscillation's amplitude when increasing the magnet's open angle α. To justify this result spectral analyze of both back-EMF and flux is done which shows remarkable changing in the different harmonics amplitude. The THD (total harmonic distortion) of flux is calculated for different α searching the optimal value which achieves $\min_{\alpha}(THD)$ [2]. $\Delta T/T_{average}(\psi_e)$ Curves, correspond to some values of α are presented in figure 4.

D. Flux weakening regions

This paper investigates also the effect of magnet's open angle (α) on the characteristic torque-speed of the machine, starting by the calculation of L_d, L_q which directly define the flux weakening capability and possible speed range. This calculation is done for three load's currents taking into consideration iron saturation. Figure 5 represents the values of L_d, L_q according to the magnet's open angle. Previous calculation allows to determine and to compare the flux weakening regions which corresponds to different magnet's open angles. The results show that rotor with straight magnet poles ($\alpha = 180°$) gives wider flux weakening region. In this study we keep always the same magnet volume, but it worth to mention that V-shape magnets allow installing bigger magnet's segments which give more torque at low speed thanks to higher linkage, but in the same time bigger magnets lead to shorter flux weakening region due to the decrease in d-axis inductance [3].

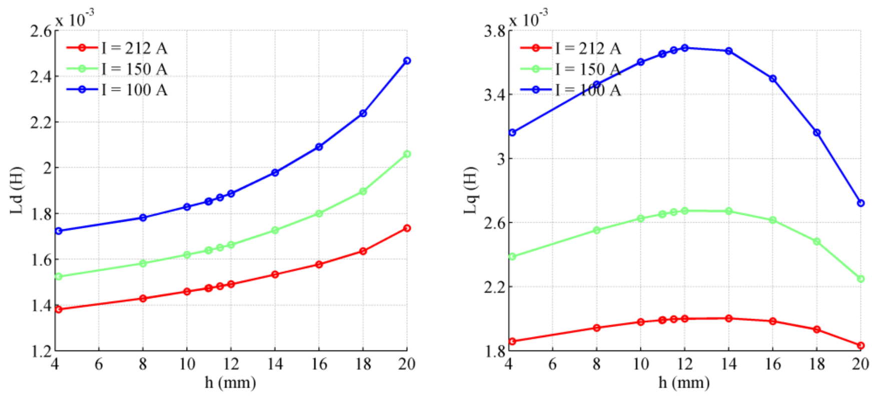

Figure 5. Direct and quadrature inductance for different h values.

II. MACHINE WITH V-SHAPE MAGNETS FIVE-PHASE

The idea of comparison between the machine PRIUS and a five-phase machine is to examine the effects of the phase's number on the characteristics of the machine, while keeping the same dimensions and structure. In order to make PRIUS machine capable to have 5-phase integral slot stator winding, 8 slots were deleted from its stator to have 40 slots instead of 48, then we get 1 slot per pole and per phase.

The average torque of this machine does not differ notably from PRIUS, when injecting a first harmonic current, but the interesting expected result was the small relative amplitude of torque ripple comparing to three-phase machine PRIUS [4]. We found also that in the machine five-phase, torque oscillation is less affected by the magnet's open angle. At last, after investigation how the magnet's open angle affects the distribution of harmonics in the Back-EMF, an optimization method is applied to search ($\alpha_{optimal}$) which maximizes the Back-EMF harmonics capable of generating more electromagnetic torque ($harm_1$, $harm_3$), while minimizes the others [5]. Then by injecting the suitable current harmonics, optimal torque could be obtained.

CONCLUSION

This paper studies the effects of magnet's open angle on the first and second order characteristics of PRIUS machine type and similar five-phase machine. In PRIUS machine type magnet's open angle equal to 139.05° gives minimum cogging torque. Torque ripples increase notably with magnet's open angle. The inductance values L_d, L_q vary also with this angle leading to different flux weakening regions. This study shows that structure with straight magnets (open angle = 180°) has wider flux weakening region than V-shape types.

Five-phase machine has smaller relative torque ripple than PRIUS machine type. In addition, the torque oscillation of this machine is less affected by the variation of magnet's open angle. At last, in this paper, additional back-EMF harmonics produced at certain optimal magnet's open angle will be used to generate more torque.

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