Analytical Design of a High-Torque Flux-Switching Permanent Magnet Machine by a Simplified Lumped Parameter Magnetic Circuit Model

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Abstract -- This paper presents how to analytically design ahigh-torque three-phase flux-switching permanent magnet machine with 12 stator poles and 14 rotor poles. Firstly, the machine design parameters are studied addressing on high output torque and its flux distribution is also investigated by finite-element method (FEM) analysis. Then a simplified lumped parameter magnetic circuit model is built up for analyzing design parameters. And a design procedure is also presented. The analytically designed machine is verified by FEM simulations.

INTRODUCTION

FLUX-SWITCHING permanent magnet (FSPM) machines having PMs in the stator with doubly salient stator and rotor structure like a switched reluctance machine combine the advantage of a conventional PM machine and a switched reluctance machine. They have therefore high reliability, high torque /power density and relatively high efficiency, hence preferable for reliability premium applications. Today FSPM machines have been presented for different applications, such as in aerospace, automotive and wind energy applications [1]-[3]. Several papers have investigated different FSPM machines with various stator and rotor pole combinations and their characteristics [4]- [11]. In [4] and [9] a FSPM machine with 12 stator poles and 14 rotor poles (12/14 poles) as shown in Fig. 1 has been investigated. Compared with a 12/10 pole machine, this machine can provide higher torque densitywith less torque ripple

Today FSPM machines are generally designed as aninitial machine, in which Hsb = lpm = Wrt = Ws = Wst = τs /4 as shown in Fig. 2, thereafter the optimal parameters and /orperformance were studied by either finite element method (FEM) simulations or lumped parameter magnetic circuit model [8] [11][14]. Such initially designed FSPM machines usually have highly saturated stator iron teeth that is normally beneficial for a 12/10 pole machine to improve the output torque. But for a 12/14 pole machine, the high saturation will lead to a torque decrease due to the high flux leakage between the stator and rotor [9]. So a new approach is required to design a high-torque 12/14 pole machine. This paper introduces a simplified lumped parameter magnetic circuit model to analytically design the machine. Firstly the machine design parameters are studied addressing on high output torque. Then the flux distribution of a typical 12/14 FSPM machine is investigated by FEM simulations, based on which a lumped parameter magnetic circuit model is built up for finding optimal design parameters. Finally, the analytically designed machine is verified by FEM simulations.

For the design of an in-wheel traction system, there are two possible topologies, namely, direct driving and indirect driving. In a direct-driving system, the electrical motor is directly driving the wheel without a gearbox, as shown in Figure 1(b). This direct-driving in-wheel module provides a maximum simplicity for the system design; thus, it is commonly adopted in most existing in-wheel traction systems.

However, due to the absence of gearbox, the electrical motor of a direct-driving system needs to provide a high torque. The high torque in-wheel motor increases the wheel mass and consequently reduces the passenger comfort [3]. To solve this problem, an indirect-driving in-wheel module, shown in Figure 2(a), can be adopted, in which the electrical motor is indirectly driving the wheel through a gearbox. By this means, the required torque for the motor is reduced (Figure 2(b)), and the wheel mass is maintained. Different topologies of the in-wheel traction lead to different requirements and constraints for the motor design. Nevertheless, in both topologies, electrical motors need to have a high torque density with certain level of ruggedness.

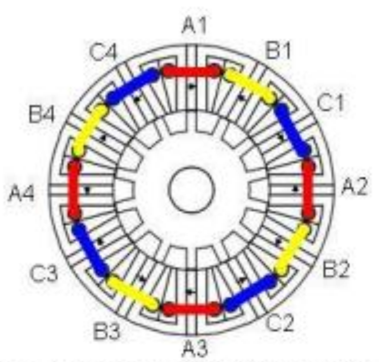

Fig. 1. Cross section of a 12/14 pole machine.

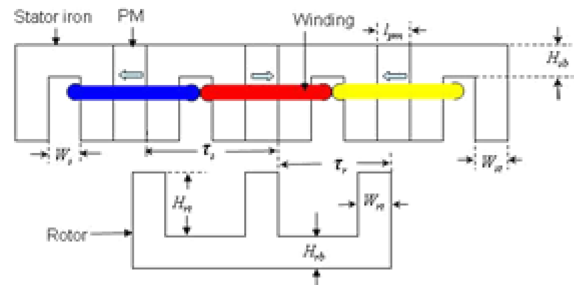

Fig. 2. Part of an initial machine in a plain form.

MACHINE CONSTRUCTION

Fig. 1 shows the machine construction. Each phase winding of the machine consists of four coils and each coil is concentrated around two stator teeth with a magnet inset in between. The magnets are circumferentially magnetized and the magnetization is reversed in polarity from one magnet to the next. For each phase the flux in coils 1 and 2 are respectively the same as that in the corresponding phase coils 3 and 4 due to the symmetrical machine construction. The coil -flux linkage of each phase (the summary of four coils) is essentially sinusoidal with respect to the rotor position and has a period of τr as shown in Fig. 3. And it reaches the peak value when the rotor is at the d-axis position of the phase as shown Fig. 4 (a). At this position the fluxes in the four coils of the phase are the same, as can be seen in Fig. 5 in which the fluxes in coils A1, A2, A3 and A4 are the same.

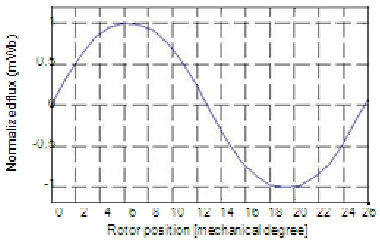

Fig. 3 Coil-flux linkage in one phase

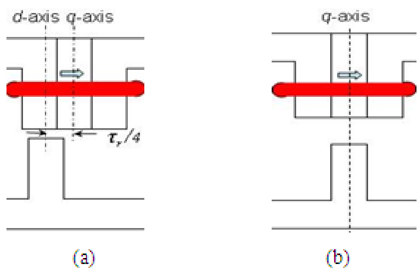

Fig. 4. Rotor at (a) *d*- axis position where the coil-flux linkage is maximum, (b) *q*-axis where the coil-flux linkage is zero.

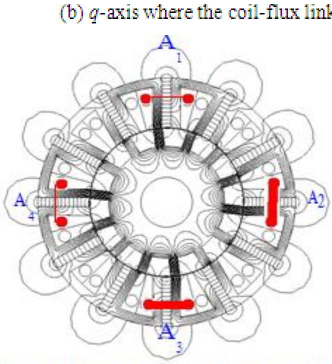

Fig. 5. Flux distribution at the *d*-axis position of phase *a*.

MACHINE DESIGN

A. Design parameters

If neglecting machine losses the torque of a 12/14 pole FSPM machine can be expressed as [9]

$$T = \frac{2\pi^2}{4P_s} k_\sigma P_r B_t \lambda^2 D_o^2 L S c_s . \qquad (1)$$

where B_t is the average flux density in the stator tooth tops at the *d*-axis position, and k_σ is the leakage factor representing the effective flux for torque production at the *d*-axis position and evaluated here by

$$k_\sigma = \frac{\Phi_{p3} - \Phi_{p4}}{\Phi_{p3}} \qquad (2)$$

where Φ_{p3} and Φ_{p4} are respective the flux through the teeth *P3* and *P4* in Fig. 8.

The parameters D_o and L are generally constrained by the available volume of a specific case and are therefore fixed. In this paper they are respectively 100 mm and 200 mm

$B_t$is an important design parameter. Ideally withoutconsidering iron saturation, the higher B_t, the higher torque from (1) would be produced. In reality, along with an increase of B_t the value of k_σ will decrease because of the increased iron saturation. This has been proven by FEM analysis as presented in Fig. 6, in which B_t is varied by using different magnet materials with various B_r from 0.6 -1.2 T, whilst keeping the machine dimension parameters unchanged. Since the output torque depends on both B_t and k_σ, their product value that directly indicates the torquecapability of the machine is also shown in the figure. It is observed that the product reaches its peak value when B_t is 1.8 ~1.9 T. With a further increased B_t the leakage flux Φ_{p4} increases more than the total flux Φ_{p3} due to the iron saturation as shown in Fig. 7. As consequence, the effective flux, Φ_{p3}- Φ_{p4}, for torque production decreases, hence the leakage factor k_σ determined by (2). In this paper B_t is chosen to be 1.8 T, which is typically the saturation flux density of iron materials.

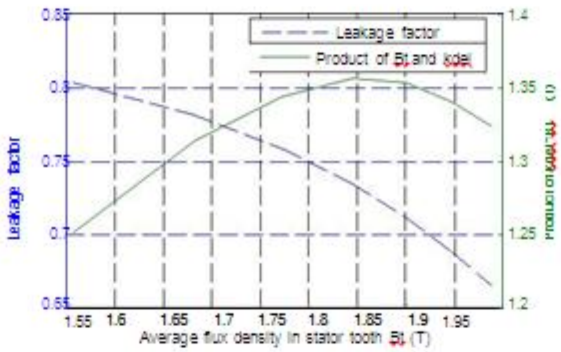

Fig. 6. k_σ and the product of B_t*k_σ as function of B_t from FEM analysis.

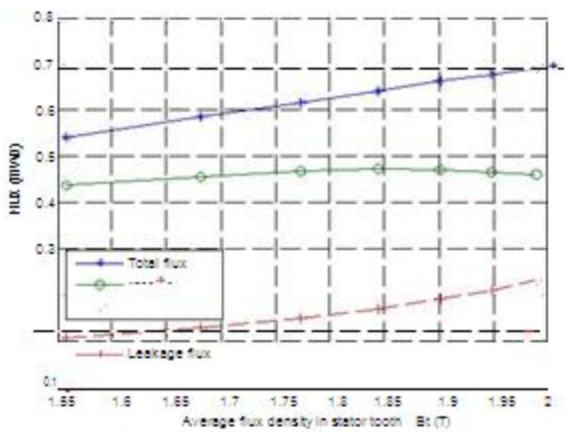

Fig. 7. The total, effective and leakage flux at different flux densi

Design procedure

To calculate the maximum output torque from (1) with certain λ and c_s, the value of k_σ should be known when B_t is 1.8 T. This is achieved by gradually increasing l_{pm} based on the given initial value, then recalculating W_{rt} from (9) and further all the permeances in Fig. 9. Thereafter, solving the model to figure out Φ_{p3} and Φ_{p4} and further k_σ and B_t. Repeating the process until B_t = 1.8 T. Now l_{pm} and k_σ are known and the output torque can be evaluated by (1).
Fig. 11 presents the design procedure

Designed machine

Fig. 12 shows the leakage factor as function of λ and c_s. For each c_s the value of k_σ increases along with an increase of λ, and for each λ there is an optimal c_s where k_σ reaches its maximum valuepresents the output torque as function of λ and c_s. There is an optimal λ and c_s giving the maximum output torque. Fig. 14 and Fig. 15 respectively show the maximum output torque with respect to split ratio λ and stator tooth factor c_s. It is found that the optimal λ is around 0.5 and c_s is around 0.25 for the discussed case here. Table I lists the parameters of the designed machine

It should be noted that the magnet demagnetization and the maximum allowable temperature of the winding insulation should be considered when selecting the current density. This is out of the scope and therefore is not discussed in this paper.

FEM SIMULATION

To verify the result, the machine with the parameters given in Table I is investigated by 2D-FEM simulations, in which the *B* -*H* curve in Fig. 10 is employed for the iron material and B_r determined by (12) is set to 1.09 T to take the temperature influence into account. Fig. 16 shows the flux distribution of the machine at the *d*-axis position with no load (J = 0), from which B_t and k_σ are obtained. Fig. 17 presents the output torque from the simulation. And Table II lists the results from both the lumped parameter magnetic circuit model and the FEM simulations. The torque calculated from the circuit model is about 3.3% higher than that from the FEM simulations. They match each other satisfactorily.

CONCLUSION

This paper has introduced a simplified lumped parameter magnetic circuit model for analytically designing a high-torque 12/14 pole FSPM machine. And the design procedure of how to find out the optimal design parameters is also presented. The design machine has been verified by FEM simulations

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