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Analytical Hybrid Model for Flux Switching Permanent Magnet Machines

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With the emergence of energy related issues in the automotive sector, there is a tendency to find new efficient solutions to replace existing electrical machinery. One promising candidate is the flux switching permanent magnet machine (FSPMM). Due to its challenging structure and nonlinear characteristic, in the investigation of the machine, generally finite element method (FEM), and rarely the magnetic equivalent circuit (MEC), are implemented. The following paper introduces an alternative analytical modeling technique by means of a hybrid model, which combines the advantages of the MEC and the Fourier analysis.

Index Terms—Flux switching, Fourier analysis, hybrid model, magnetic equivalent circuit, permanent magnet.

I. INTRODUCTION

IN almost every branch of industry, the primary aim is to find energy efficient solutions for applications at a minimum cost. In the automotive and energy sectors, there is a tendency to introduce a new class of machine, the flux switching permanent magnet machine (FSPMM) [1]. The current options in traction applications are the permanent magnet synchronous motors (PMSM) due to their high power density and switched reluctance motors (SRM) due to their simple rotor structure capable of reaching higher speeds. The FSPMM embodies these combined advantages.

The cross section of the machine is shown in Fig. 1 with the parameters explained in Table I. The stator part of the consists of 12 so called elementary cells. The basic principle of flux switching occurs in one elementary cell due to the movement of the rotor. The flux linked to the corresponding coil phase switches direction in the next rotor position, which leads to a bipolar phase flux linkage. This advantage gives an increase in the energy utilization. As illustrated in Fig. 1, the PMs are situated in the stator instead of the rotor, which leads to a prebiased structure with a relatively low demagnetization compared to the PMSM (e.g., Brushless AC). Additionally, since the rotor is only iron material, it is easier to construct and the machine requires less volume giving a higher torque density. In flux weakening mode, the machine is capable to reach relatively high speeds up to 50.000 rpm for a single phase 3-kW machine with a 30-mm rotor diameter [2].

Despite all these benefits, the design phase is a challenging task. An explicit mathematical expression of this novel machine is not available yet. Due to the FSPMM's double salient structure and saturation, most researchers prefer the finite element method (FEM). The use of analytical approaches is very rare with the only example of the magnetic equivalent circuit (MEC) method [3]. In order to provide a more accurate analytical technique, a new hybrid model is proposed for the design. For verification, the initial simulation parameters are taken similar to [3], although variations are possible.

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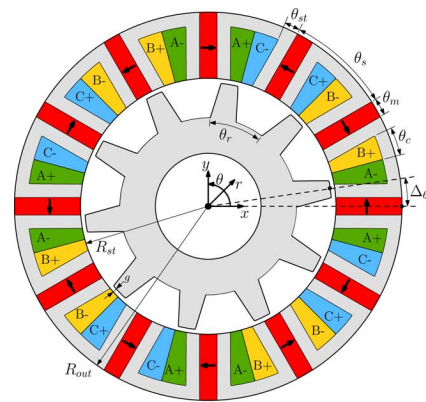


Fig. 1. Conceptual design of a 3-phase 12/10 pole FSPMM.

The modeling methodologies are discussed together with their field calculations in Section II, which form the basis for the proposed model. Consequently, Section III introduces the results of torque calculations using the hybrid model.

II. MODELING PRINCIPLES AND FIELD CALCULATIONS

One significant characteristic of the FSPMM is its nonlinear behavior. The placement of magnets and coils in the stator leads to local saturation occurrences, which is neglected in the linear analysis. Due to this saturation, the airgap flux density B values drop significantly. Extreme B values are reached in the airgap due to the flux concentration in the path of the rotor and stator teeth alignment, i.e., $B_{\max} = 2.7$ T for the linear and $B_{\max} = 2.03$ T for the nonlinear analysis.

Magnet iron is used as the ferromagnetic material in the nonlinear analysis, with the properties presented in Table I. For the nonlinear BH curve of magnet iron, an analytic saturation function is used from [4].

Focusing on these points, the hybrid model concept is explained based on two complementary models. On one hand, the MEC approach enables the investigation of saturation, however, at the cost of decreased accuracy. On the other hand, the Fourier analysis realizes an accurate investigation, however, does not include saturation.

The following subsections contain the building blocks needed to provide an accurate modeling or design tool for the FSPMM.

TABLE I
FSPMM SIZE AND PARAMETERS

N_{ph}	Number of phases	3
N_r	Rotor pole number	10
N_s	Stator pole number	12
R_{out}	Outer radius	45 mm
R_{st}	Stator radius	27.5 mm
L_a	Axial length	25 mm
g	Airgap	0.5 mm
θ_s	Angular stator pitch	$360^\circ/N_s$
θ_m	Angular magnet width	$\theta_s/4$
θ_c	Angular coil width	$\theta_s/8$
θ_{st}	Angular stator tooth width	$\theta_s/4$
θ_r	Angular rotor pitch	$360^\circ/N_r$
θ_{rt}	Angular rotor tooth width	θ_{st}
$\Delta\theta$	Mechanical displacement	θ_{st}
Δ_e	Electrical displacement	$\Delta\theta \times N_r$
N	Number of turns per phase	72
B_{rem}	Remanent flux density of permanent magnet	1.2 T
B_{sat}	Saturation level of soft mag. mat. (Magnet-iron)	2.15 T
μ_{pm}	Relative permeability of permanent magnet	1.05
μ_{max}	Magnet-iron maximum relative permeability	7000
μ_{ini}	Magnet-iron initial relative permeability	1273
I	Phase current (rms)	11 A
T	Rated torque	2.2 Nm
w_m	Rated speed	4400 rpm
P	Power	~ 1 kW

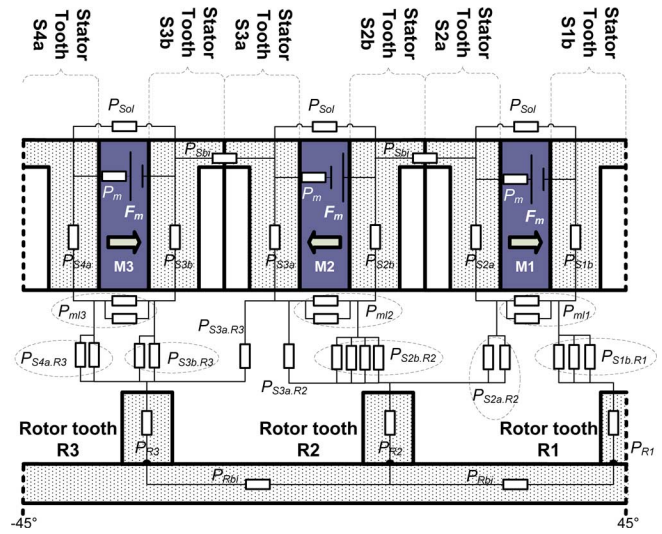


Fig. 2. MEC model of the quarter FSPM machine in rectangular coordinates.

TABLE II
ELEMENTS OF THE MEC MODEL

F_m	Magnet mmf
P_m	Magnet permeance
P_{Sol}	Stator outer leakage permeance
P_{ml}	Magnet leakage permeance
P_{Sbi}	Stator back iron permeance
P_{S1a}	Stator tooth permeance of stator cell 'S1' and stator tooth 'a'
P_{S1aR2}	Airgap permeance combining the stator tooth 'S1a' with the rotor tooth 'R2'
P_{Rbi}	Rotor back iron permeance
P_{R1}	Rotor tooth permeance of tooth 'R1'

A. Magnetic Equivalent Circuit (MEC) Model

MEC modeling is especially useful when saturated structures are investigated, e.g., FSPMM. The machine in Fig. 1 exhibits a half symmetry, despite to it, for the rotor position $\Delta\theta = 9^\circ$ a symmetrical behavior is observed in the magnetostatic open-circuit analysis. This position is related to the maximum flux linkage in phase-A. Under these assumptions, the FSPMM is modeled as quarter machine for the MEC model [3]. Additionally, the MEC model can be simplified due to the high number of poles of the investigated machine, which allows the use of rectangular coordinates without significant loss of accuracy. The techniques for the MEC used in this paper, are based on [3] although some improvements were necessary.

All the permeances are calculated via

$$\mathcal{P} = \int \frac{\mu_0 \mu_r dS}{l} \tag{1}$$

with μ_0 is the air permeability, μ_r is the relative permeability of the concerned medium, S the cross section of the considered flux tube, and l is the distance travelled by the flux tube. The most difficult part is to determine the airgap permeances. Due to the double salient structure seen in Fig. 2, a high number of different flux paths has to be approximated in the airgap. The elements in Fig. 2 are explained in Table II. To increase the accuracy of the MEC model, the airgap permeances \mathcal{P}_{ml} and \mathcal{P}_{S1aR2} are written explicitly as parallel permeances and due to the open-circuit analysis the slot leakage permeances are neglected. These parallel permeances, encircled in Fig. 2, are approximated according to the assumptions in [5].

The results for field calculations using the MEC model are given in Fig. 3(a) and (b), for the linear and nonlinear cases respectively, and verified by the FEM. Both cases show a good agreement. The reason for the smoother FEM results is the more dense numerical space mesh, whereas the MEC technique only uses space mesh formed by the magnetic equivalent permeances.

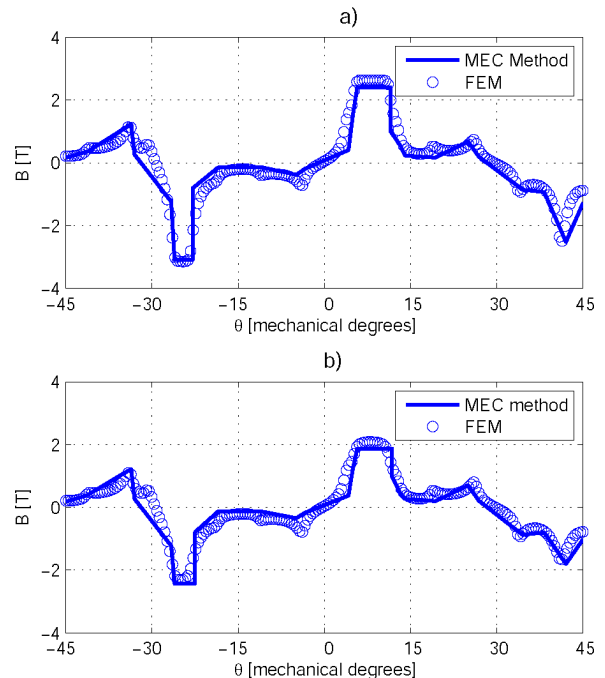


Fig. 3. Open-circuit airgap magnetic flux density comparison for $\Delta\theta = 9^\circ$ (a) in the linear analysis quarter machine and (b) in the nonlinear analysis of quarter machine.

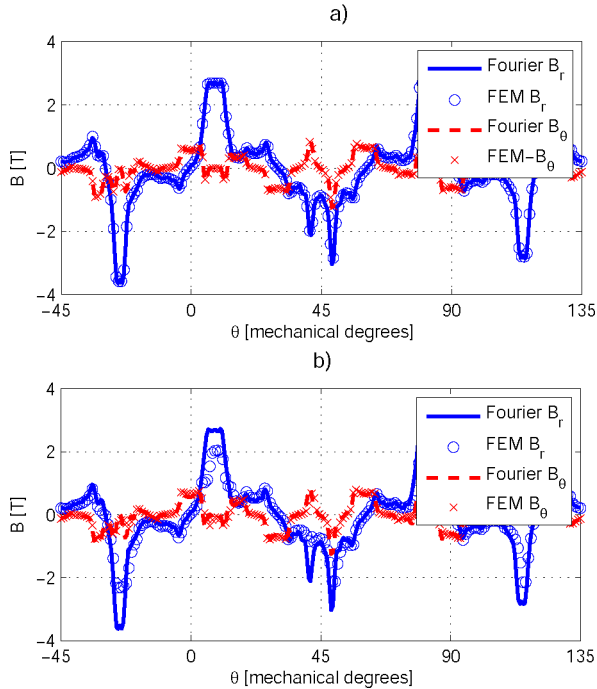


Fig. 4. Magnetic flux density comparison in the center of airgap including the armature reaction for $\Delta\theta = 9^\circ$ (a) in the linear analysis half machine and (b) in the nonlinear analysis of half machine.

B. Fourier Model

Fourier analysis is based on harmonic notation of the electromagnetic fields. Among several studies in this topic, [6] provides a general framework suitable for modeling of the FSPMM. For the 12/10 pole machine, half periodicity is implemented using polar coordinates ($r - \theta$).

In this method, iron parts are assumed infinitely permeable and the machine is divided into regions according to their tangential boundary conditions. These can be of periodic or Neumann type, where the tangential magnetic field strength H component is zero. Therefore, the rotor and stator back-iron parts are not considered as regions, but only represented by boundary conditions. For the FSPMM, the considered regions are rotor teeth slots, uniform airgap, magnets, coils, and surrounding air.

The flux density calculations shown in Fig. 4 are verified with the FEM in the center of the airgap. A good agreement regarding both the normal and tangential components is obtained in Fig. 4(a). This agreement is better than the linear MEC-FEM agreement due to the higher level of accuracy of the Fourier approach. However, in Fig. 4(b), this agreement is lost due to the fact that the Fourier analysis does not take into account for saturation of the soft magnetic material.

C. Hybrid Model

Combination of the MEC and Fourier analysis create the basis of the analytical hybrid model. The main idea of this model, as illustrated in Fig. 5, is capturing the nonlinear behavior of the FSPMM by virtually changing one geometrical parameter. This parameter is referred as x and can be taken for example as airgap

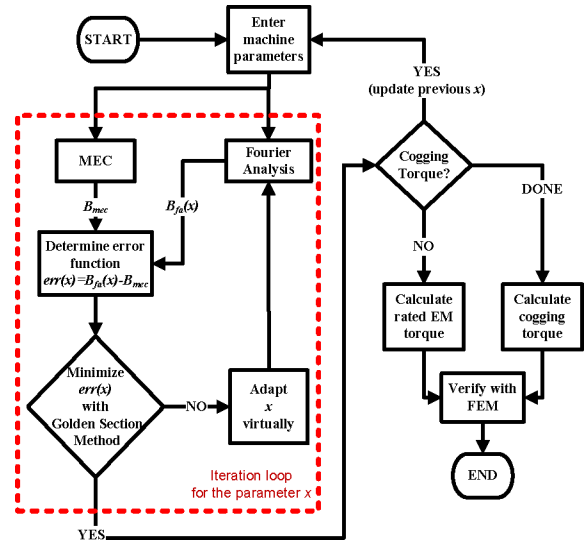


Fig. 5. General block diagram of the hybrid analytical model.

length or coil slot width, depending on what has to be calculated with the hybrid model.

In the model, firstly the machine parameters given in Table I are initialized. Next, the reference flux density values are obtained from the nonlinear MEC model, while the Fourier model calculates the initial normal component B_r of the magnetic flux density on the points where the permeances from the MEC model are defined. These values are calculated for the initial x , i.e., the initial airgap length g is taken as x to calculate the rated torque output. Afterwards, the iteration to obtain the right g for the best MEC-Fourier model agreement starts and continues until the predefined error function is minimized numerically by the Golden Section Method [7]. This method is especially chosen due to its simple implementation and suitability for cases where the numerical optimization is independent of the investigated error function's structure. However, other iteration methods could be applied as well.

While the airgap length varies, the rotor diameter is adapted accordingly. Since this part solely consists of iron, it was a logical choice to adjust rather than the total machine diameter. Once the airgap flux density distribution is known, the average electromagnetic torque output can easily be calculated with the Fourier analysis for the virtually adapted geometry. If additionally a cogging torque simulation has to be considered, after updating the g value by g_{new} from the rated torque calculations, the iteration loop in Fig. 5 reruns in the same logical order as previously until the optimum parameter x is achieved. For the cogging torque calculation, this parameter x could be magnet width θ_m , coil slot width θ_c , stator tooth width θ_{st} or rotor tooth width θ_{rt} . Among these, θ_c is chosen due to its easy optimization in the mathematical model.

The iteration loop is the most crucial part of the hybrid model; therefore, for the error function in Fig. 5, three possibilities have been proposed. The first two error functions consider a point-wise comparison referred to as hybrid criteria A and B. Criterion A compares the field solution from the MEC and the Fourier analysis only at the positions where a

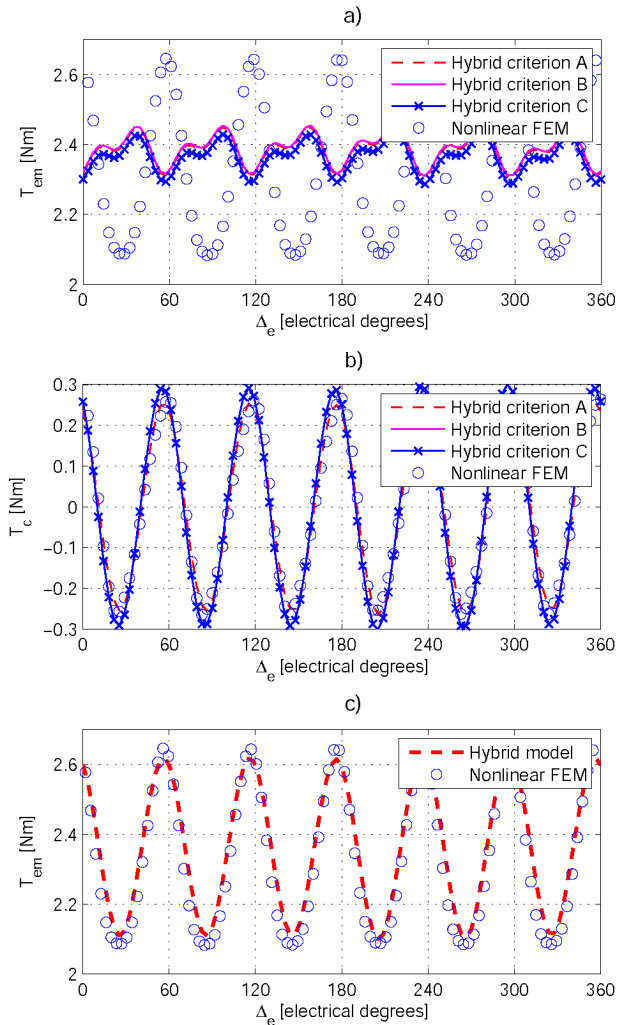


Fig. 6. Verification of the (a) rated torque analysis, (b) cogging torque analysis, and (c) electromagnetic torque analysis calculations obtained from the hybrid model.

magnetic flux density above 2 T is calculated. The reason to compare only at these points is that the field distribution from the Fourier model gives the most obvious deviation at these maxima-minima points, as shown in Fig. 4(b). In the second iteration loop where the θ_c is varied, this limit is decreased to 1 T due to the higher g_{new} compared to the initial g value, which leads to a general decrease of the airgap flux density distribution. Criterion B takes the whole airgap points into account. The third error function, hybrid criterion C, compares the integration of the absolute flux density over the airgap from the MEC and Fourier analysis.

III. TORQUE CALCULATION RESULTS

Among various torque calculation methods available in the literature, Maxwell Stress Tensor (MST) is chosen. The Fourier analysis gives very accurate analytical expressions for both the normal B_r and tangential B_θ magnetic flux density components. With the MST method, an analytical torque expression is obtained using these analytical solutions of B_r and B_θ .

Based on the three different predefined error functions, first the rated torque output is calculated. Although in Fig. 6(a), all three methods give very similar results, the best approximation of average torque is reached by the hybrid criterion C with a mean average percentage error of 1.12% and simulation time of 23 s. Next, the cogging torque calculation using g_{new} from Fig. 6(a) is presented in Fig. 6(b), where a very good agreement is achieved but this time with the criterion A. Finally, combining Fig. 6(a) and (b) leads to the electromagnetic torque calculation as given in Fig. 6(c), resulting a perfect agreement with the FEM.

IV. CONCLUSION

Flux switching machines are at a first glance very promising alternatives to replace PMSM (e.g., BLDC) and SRM; however, the dearth in analysis and design tools give that it is very difficult to automate the optimization routines. With the proposed hybrid analytical model, the advantages of the nonlinear MEC model are combined with the high accuracy of the Fourier method to provide a very fast analysis tool. This new model is capable for predicting the magnetic flux density, cogging and rated torque outputs. It does need noting, that the use of MEC also limits the general applicability of this analysis tool, and, therefore, other methods are currently under investigation.

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