The Working Principle of Flux Switching Machines

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This work is about clearly illustrating the working principle of flux switching machines. In the past, different topologies regarding stator-/rotor configurations were presented and evaluated. Moreover, optimization of the operational characteristics was considered. The focus was on optimizing the shape of utilized components. However, the principle of torque generation is not clear at first sight, as typically the number of poles of the magnetic field due to the permanent magnets and due to the winding arrangement are not of same number. The reason for generating a net torque considering an entire period is the flux modulation due to the rotor teeth. A thorough explanation is presented featuring both, theoretical aspects as well as numerical studies utilizing finite element simulations. Results can help to derive general understanding of the working principle and will facilitate the development of new configurations.

***Index Terms*—finite element method, flux modulation, flux switching machine, magnetomotive force, 2-D FFT**

I. Introduction

Analyses of flux switching machines were started long time ago. In the 1950s, flux-switch alternators with four stator and six rotor poles were discussed [1]. The today's most investigated topology features 12 stator slots, an interior rotor with 10 rotor teeth [2] and is of radial-flux type. Figure 1 gives an example. As can be observed, the stator teeth hold buried permanent magnets, while the magnetization direction of the magnets changes for two consecutive stator teeth. While this flux switching permanent magnet machine (FSPMM) is the most conventional one, nowadays various design variants are analyzed, e.g., Vernier-like configurations [3], variants with DC current excitation [4], or even tubular structures [5]. The research typically is focused on modeling and optimization of particular configurations and slight attention is paid to the basic working principle. However, it might not be clear at first sight why a 12 pole field due to the permanent magnets and an 8 pole winding configuration, as depicted in Fig. 1, will generate a mean torque when combined with a rotor featuring 10 teeth. In the following, a thorough explanation is presented disclosing the 'secret' of torque production in FSPMMs.

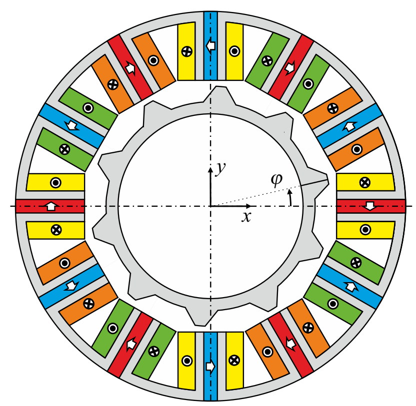


Fig. 1: Standard permanent magnet flux switching machine configuration: The stator holds a three-phase double-layer winding within 12 slots. Permanent magnets are buried in the stator teeth with alternating tangential magnetization direction. The rotor is made of lamination only and features 10 teeth.

II. Working principle

In the past, authors did analyze the linked flux and flux density in the air gap, especially when dealing with unconventional 6 slot / 4 pole - configurations [6]. Usually, the no load and load characteristics for a particular machine design are considered.

Here, we investigate how the flux switching machine can generate torque, even though the field due to the permanent magnets and the one due to the stator currents has a different number of poles at first. Generally speaking, the rotor angle-dependent torque T of a radial flux machine can be expressed by

$$T(\alpha) = \frac{r^2\, l}{\mu_0} \int_0^{2\pi} B_r(\alpha,\varphi)\, B_t(\alpha,\varphi)\, \mathrm{d}\varphi \ , \qquad (1)$$

where α gives the rotor angle, φ the spatial circumferential position, r the radius of the air gap, l the axial length of the motor and μ_0 the absolute permeability of air. Consequently, B_r and B_t are the radial and tangential component of the flux density.

As can be observed from (1), to generate a net torque for some rotor angle α, a radial and tangential flux density of same spatial harmonic order must be present in the air gap field.

Moreover, when considering the mean torque $\overline{T}$ for one rotor revolution, defined by

$$\overline{T} = \frac{1}{2\pi} \int_0^{2\pi} T(\alpha)\, \mathrm{d}\alpha \ , \qquad (2)$$

it becomes clear that the two flux density components B_r, B_t must further show same order regarding the rotor movement also to provide net torque instead of just a zero-mean torque ripple. This must also hold for the flux switching machine, even though at first sight its net torque production is not obvious.

A. Flux modulation principle

Similar as for the magnetic gear [7], it can be concluded that a FSPMM can generate net torque if

$$p_c = |p_{pm} \pm n_r|. \tag{3}$$

p_c and p_{pm} give the original number of pole pairs of the field due to the currents of the stator windings and the permanent magnet excitation, respectively, while n_r defines the number of rotor teeth. Table I gives commonly used stator slot-/rotor teeth-configurations n_s, n_r, including the original number of pole pairs of the two field components and the modulation of the permanent magnet field p_{mod}. It can be observed that, due to the modulation, p_{mod} = p_c for both topology 1 and 3.

TABLE I: Common FSPMM configurations

topology	n_s	n_r	p_c	p_{pm}	p_{mod}
1	12	10	4	6	$\|6-10\|=4$
2	12	14	4	6	$\|6-14\|=8$
3	6	4	1	3	$\|3-4\|=1$

For topology 2 of Table I, p_{mod} does not match the number of poles of its p_c counterpart. However, p_{mod} is a multiple of p_c and the torque generation of the 12/14-configuration is not due to the magnetomotive force (mmf)-harmonic of the first order of the winding configuration, but due to its second order. For the same reason, the winding configuration must be changed from A, B, C to A, C, B when switching from topology 1 to 2, as it was done in [8]. Otherwise, the rotor would move in the other direction, as first and second order mmf-harmonics cause flux density waves moving in opposite circumferential direction when considering sinusoidal symmetric three-phase current supply.

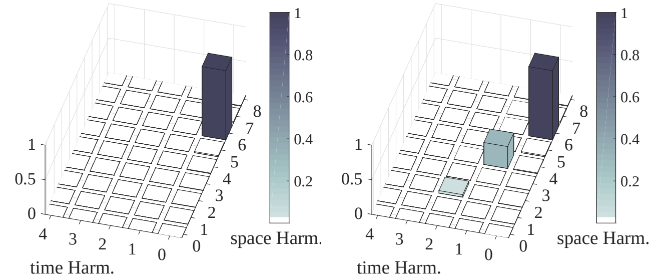
B. FE-based analysis

In order to verify the proposed theory, a FE-based analysis is performed. Simulations are examined for having only the stator current excitation or only the permanent excitation set to non-zero. To understand the principle of flux modulation, either a standard rotor with teeth or a rotor featuring no teeth but a ring-shaped cross section is applied. The latter one obviously cannot be used to generate torque, but it is selected for investigating the flux density characteristics when no flux modulation due to the rotor is present. Table II gives a definition of the considered simulations, i.e. which sources for the magnetic field are non-zero and which rotor type is used.

TABLE II: Investigated FE-simulations
(all for a standard 12/10 FSPMM configuration)

sim. index	pm-exc.	stator curr. exc.	rotor
1	present	not present	ring-shaped cross section
2	present	not present	standard rotor with teeth
3	not present	present	ring-shaped cross section
4	not present	present	standard rotor with teeth

In Fig. 2 a comparison of the 2-D FFT-Plots of the air gap flux density of simulations 1 and 2 is presented. Using a ring-shaped cross section for simulation 1 gives a permanent



(a) Simulation 1 (b) Simulation 2

Fig. 2: Comparison of the two simulations for the permanent magnet excitation using a 2D-FFT for (a) a ring-shaped rotor cross section and (b) the rotor with teeth. A significant constant flux density component is observed, while, due to the rotor teeth caused flux modulation, additional harmonics of order 4/1 arise, which will finally be utilized for torque generation.

magnet field that has a significant spatial harmonic of order 6 which obviously does not change with regard to the rotor angle, as the rotor is symmetric in circumferential direction. By contrast, using a standard rotor with 10 teeth for simulation 2 follows a flux modulation. A significant spatial harmonic of order 4 can be observed that will move with the same speed along the circumference as the rotor does. More results and the evaluation of the stator field and combined analyses will be presented at the conference and in the final submission.

Acknowledgment

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