

Performance analysis of a two-module reluctance motor with an axial flux

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The paper presents simulation results for a two-module reluctance motor (Transverse Flux Motor) with an outer rotor. The two-module TFM construction is compared with a classical, three-module one. A specific shape of teeth is used to obtain a non-zero start torque. Calculations of the magnetic field and electromagnetic torque are performed using the Flux3D package based on the finite element method. In particular, the paper analyses the influence of the new motor magnetic circuit construction on the torque produced by the motor and its pulsations. The calculations enable to determine electromechanical parameters for a specific motor under design without making its costly prototype. A number of computer simulations are carried out and the results are compared with the three-module prototype version of the motor .

1. Introduction

Transverse flux motors (TFMs) have recently attracted remarkable interest both from the academia and various industrial environments [1, 3, 5, 6, 9, 10, 11]. The low-speed motor is characterized by a high ratio of the electromagnetic torque to its volume [2, 4, 11], leading immediately to various high-torque transmission-free applications, to mention electric wind generators [1], electric (and hybrid) drives [11] and in-wheel drives [3, 9]. On the other hand, there has been a tremendous effort devoted to the problem of reduction of accompanying torque pulsations, which have been plaguing not only TFMs [2, 4, 5, 7]. Reduction of the torque pulsation is certainly welcome in the above high-torque implementations, but it is vital in modern control and robotics applications [5]. Simultaneous maximization of the average electromagnetic torque and minimization of the ripple torque is a contradicting task which can only be solved in a compromise way for a specific TFM construction.

In the previous papers by the authors [6, 8, 9], principles of operation of the three-module motor, performance prediction and an effective three-dimensional analysis of the magnetic field distribution for a TFM have been presented. Specifically, an influence of selection of various sets of three-module TFM construction parameters on the electromagnetic torque and its pulsations has been comparatively examined. The simulation results were in good agreement with

experimental data obtained from the prototype motor, which confirmed the usefulness of the computational approach.

In order to additionally improve electromechanical parameters and efficiency of TFMs, the new construction of a two-module reluctance motor was designed. This work is an extension of the related topics presented in the area in Refs. [6, 8, 9]. This paper analyzes selected constructions of two-module TFMs. This motor structure has main defect – the start torque of the motor is equal to zero for specific rotor positions. This paper offers a new solution to this problem.

An effective tool for the calculation of motor integral parameters is the 3D FEM and an adequate modeling environment is the Flux3D program. It should be stressed that the modeling tool enables to avoid constructing and verifying a number of physical motor prototypes, which could be very expensive.

2. Construction of the two-module motor

The prototype motor structure is shown schematically in Figs. 1 and 2. The considered motor consists of two identical modules in which the stators are shifted by fifteen mechanical degrees between each other. The rotor modules are placed symmetrically. Each module has twelve teeth and includes one phase of winding in a shape of solenoidal coil. The rotor and its teeth are made of solid iron. The modules are insulated from each other with nonmagnetic separator. Two stator modules are centered along the motor shaft.

The main specifications for the motor are given in Table 1.

The analysis presented in this work was carried out for a small, low-voltage (24 V), two-phase TFM with an outer rotor. A number of turns of one phase coil was equal to 130 and the rated current value in calculation was assumed to 12A.

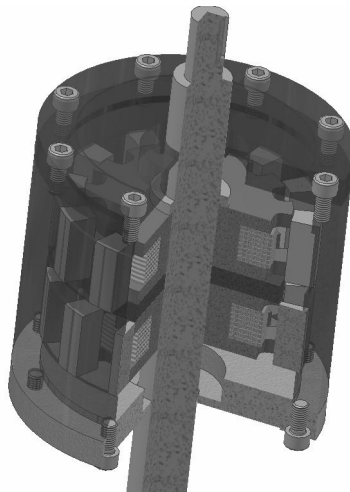


Fig. 1. Two-module TFM prototype

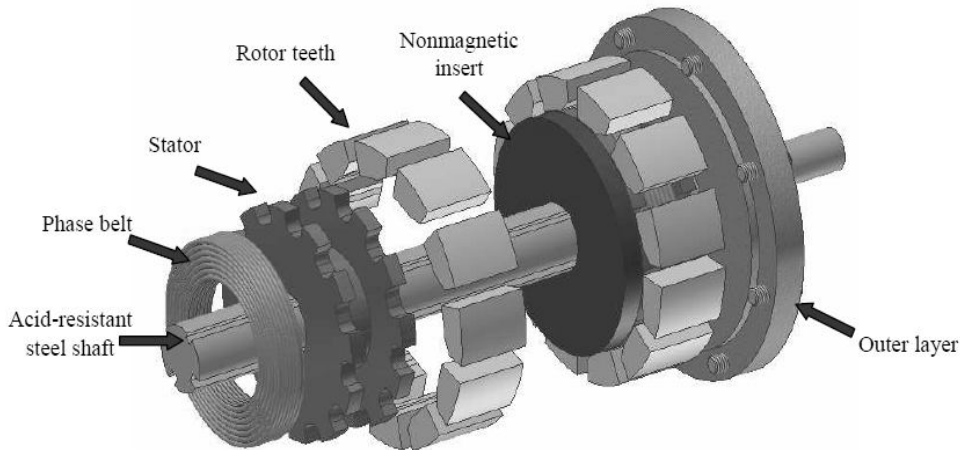


Fig. 2. Two-module TFM structure

Table 1. Specifications for TFM

Supply voltage	$U_n=24V$
Rated current	$I_n=12A$
Rotational speed	0÷300 rpm
Winding	Two-phase
Number of turns	130
External diameter of rotor	158 mm
External diameter of stator	103.5 mm
Air gap	$\delta=0.5$ mm

A simplified topology of circulation of the main flux is shown in Fig. 3, which illustrates the operation principle of the machine. The motor operates as a two-phase machine in the auto-piloted mode. The motor is supplied from a DC source through a two-pulse electric inverter (see Fig.4). Control of the motor reduces to supplying the phases with a rectangular current waveform according to the sequence A,B,A. Connection of any phase results in adequate positioning of the rotor with respect to the stator (the teeth are aligned). Since the rotor sectors are shifted between each other, the successive connection of the phases causes the rotor to rotate. The connection of the successive phases is triggered by the signals from two transoptor sensors located in the external module. The sensors co-operate with a light-reflecting disc mounted onto an inner wall of the rotor.

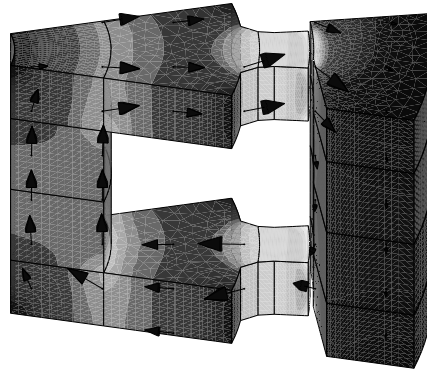


Fig. 3. Simplified topology of magnetic flux circulation

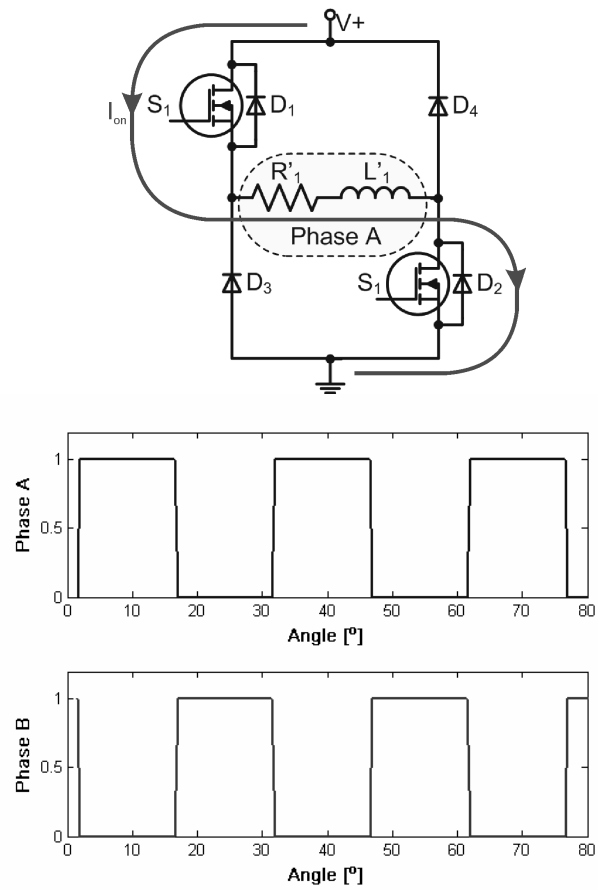


Fig. 4. One-phase half-bridge supply system and phase currents

It is worth mentioning that we have constructed the two-module prototype according to the state-of-the-art and using our long-year experience, also resulted from our previous, three-module prototype constructions [4, 9]. However, no formal optimization tools were available to us at the time of the construction of the prototype. The basic three-module motor will be used as a platform for verification of adequacy of a numerical model.

3. Numerical model

A precise numerical FEM model of the motor is developed in the Flux3D program [4, 9]. The 3D modeling package uses B-H characteristics to relate flux density with field intensity for all the materials. For the stator core and the rotor steel, the characteristics are defined in the first quadrant, with the initial values of B and H being both zero.

The analysis of the magnetic field in the 3-D space is performed under the following assumptions:

- the field is considered to be magnetostatic,
- eddy-currents in construction parts of the motors are omitted,
- eddy-current losses in rotors are negligible,
- the current density within the cross section of the coils is uniform,
- the rotational speed of the motor is constant,
- there are no magnetic couplings between individual modules of the motor.

The assumptions enable to limit the calculations to a single module only, and taking additionally account for the symmetry conditions in the motor, to 1/48 of the motor volume, which is called a calculation segment or just a segment. The structure of the two-modular motor module and the discretization mesh for the numerical model are depicted in Figs. 5 and 6, respectively. The total number of hexahedral elements in the mesh is equal to 59,053. The electromagnetic torque is calculated by the virtual work method as a derivative of the magnetic coenergy with respect to the rotation angle between the rotor and stator. The rotation of the rotor vs. stator is modeled by the sliding surface method [6, 9].

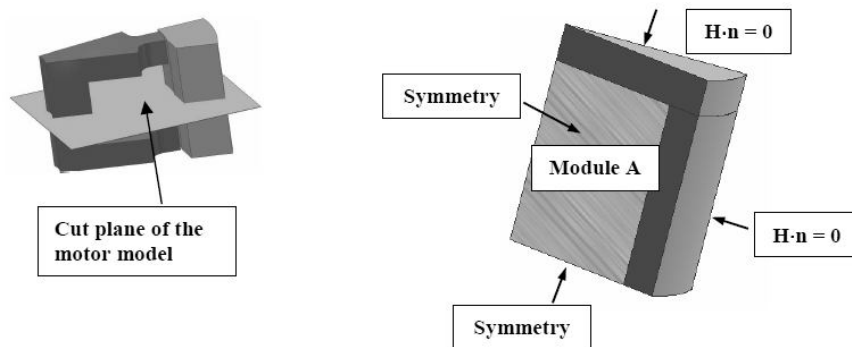


Fig. 5. Construction of TFM numerical model with boundary conditions

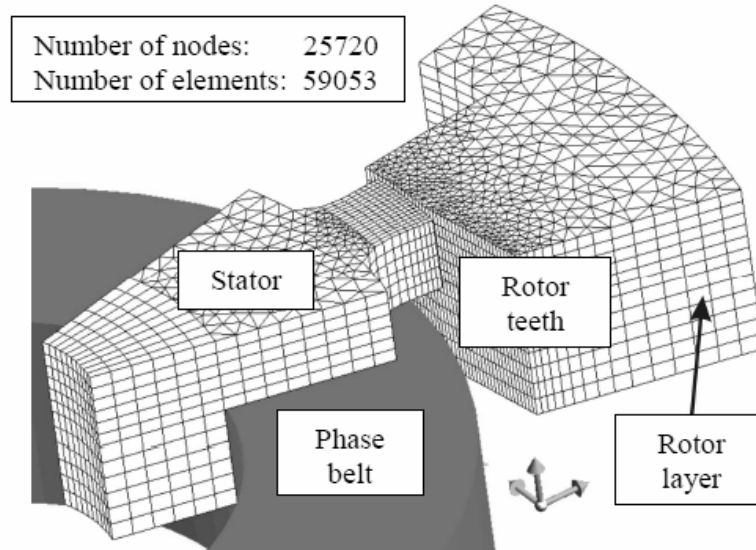


Fig. 6. Discretization mesh for TFM segment

The useful ripple torque factor ε was defined:

$$\varepsilon = \frac{T_{\max} - T_{\min}}{T_{av}} \cdot 100\% \quad (1)$$

where T_{\max} , T_{\min} and T_{av} are the maximum, minimum and average torques, respectively (in the range of a phase switch-over).

A number of two-module motor numerical models with different geometry of the rotor teeth have been performed. The example of construction of the motor module with construction parameters are presented in Fig. 7. The influence of construction teeth shape (parameters: β_1 , β_2 , l_w) on electromechanical torque was analyzed for the machine with numbers of teeth in the stator and rotor being equal to 12. This was connected with a low cost of exchanging those elements in the motor and obtaining a new construction of the prototype.

The values of basic construction parameters of the motor prototype are presented in Table 2.

Table 2. Fundamental parameters of the motor prototype

r_0 [mm]	r_1 [mm]	r_3 [mm]	r_4 [mm]	l_z [mm]	r_m [mm]	l_m [mm]	α [°]	β_1 [°]	β_2 [°]
15	23	49,75	50,25	6	62,25	32	15	15	7,5

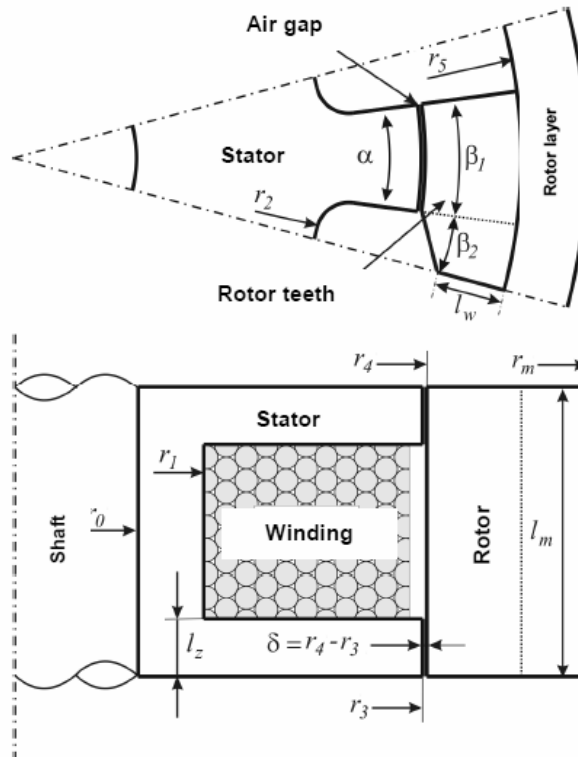


Fig. 7. Cross-section of the TFM segment

4. Results of calculations

Using Flux3D, integral parameters are calculated for the above two-module motor model. The calculated electromagnetic torques for the considered TFM models are listed in Table 3. The rated current for which the calculations are made is equal to 12A.

Calculations of the electromagnetic torque vs. rotation angle for various TFM versions are illustrated in Fig.8. In general, a remarkable reduction in average electromagnetic torque of the two-module motor can be observed. The calculation results are in good agreement with measurements on the physical motor models.

Table 3. Calculated integral parameters for TFM models

TFM	T_{\max} [N·m]	T_{av} [N·m]	γ [°]
Two-modular	5,02	2,82	17,5
Three-modular	5,69	4,06	15

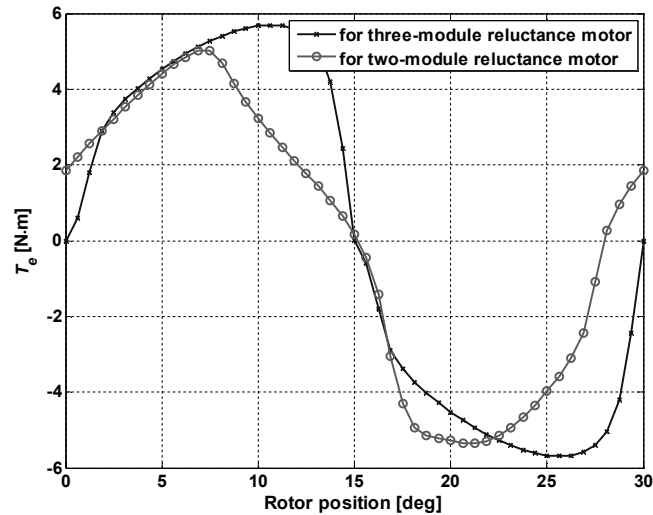


Fig. 8. Electromagnetic torque vs. rotation angle for various TFMs

The main determinant of the teeth shape usefulness in the two-module motor is obtaining the extension of a range of positive values of the electromagnetic torque produced by the motor. A larger range of angles for positive values of the electromagnetic torque guarantees the start of the motor for all rotation positions between the rotor and stator.

As can be seen from Fig. 8, the plot of electromagnetic torque for the two-module motor vs. rotor position is asymmetric. In this case (see Table 3), the extension of the electromagnetic torque range by some 2.5° results in the reduction of the average electromagnetic torque by as high as some 30% (as compared to the three-module motor).

It seems from the above results that the application of a two-module TFM does not have to necessarily lead to the increase in electromechanical parameters of the motor. In case of a slight improvement of the integral parameters of TFMs, construction of such types of the motor may be profitable from the viewpoint of construction costs. The model, due to its specific structure is characterized by high level of torque pulsations.

5. Conclusions

In this paper, a new construction of a two-module TFM has been analyzed. It has been shown in the calculations based on a precise 3D numerical TFM model that it was possible to determine a specific teeth shape and obtain the non zero start torque for the motor under design, without making its costly prototype. A number of computer simulations were carried out and the results were compared with those

for the three-module version of the motor. A selection of an appropriate configuration depends on a specific application of the motor. It is worth noticing that a number of the motor modules and their mutual rotation can also affect both the electromagnetic torque and costs.

Further improvement of integral parameters of two-module TFMs can be obtained by employing a formal construction optimization procedure, e.g. like the one in Ref. [4, 5, 8], which will be the subject of a future research work.

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