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The electromagnetic calculations of complex motion common magnetic circuit electromagnetic converter

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Abstract: This document contains results of research on complex motion common magnetic circuit electromagnetic converter characteristic that allows making independent axial and rotary shaft motion. The converter in addition to linear-rotary mechanism consists of two drive rotors and one common magnetic circuit excitator. Such a solution allows to reduce volume of the machine and makes it easier to use. The paper cites design intent and possible structure of the device. Phenomenon of common magnetic circuit adverse effect on correct operation of device is discussed. The concept of using relative error as a way to evaluate the influence of that phenomenon in the torques is discussed. Waveforms of determined relative errors for all possible cases is presented. Furthermore the concept of average relative error is defined and its use as a quantitative method of assessing the degree of common circuit impact is indicated. Definition of relative error ripple factor is given, and its usage is shown. Winding inductance calculation based on free FEM application is shown and its influence on control strategy and power system.

Key words: electrical machines, common magnetic circuit, torque relative error

1. Introduction

This document contains results of research on complex motion common magnetic circuit electromagnetic converter that allows making independent axial and rotary shaft motion (Fig. 1). The mechanical actuator of converter is linear-rotary mechanism. This solution is known and available in a few commercial solutions [5]. This mechanism needs two sources of torque to drive. The first one for rotary motion, the second for axial motion. So far, there were known applications consisting two stator-rotor units. The aim of the work is to develop a design composed of rotors and one common stator. The accurate construction description [1, 4].

Described fragment issue focuses on winding inductances, torques and on the influence of common magnetic circuit on independent drive source. Computational works were based on reluctant motor philosophy [2, 3]. This construction can be divided into inner and outer part. The outer part consist of a rotor with six teeth and outer part of the stator with eight teeth. On the stator teeth winding coils are located. Winding is associated with four phases (A, B, C, D).

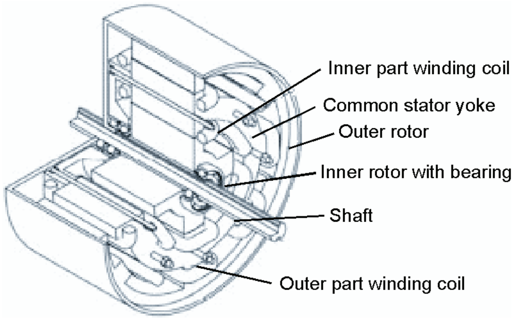

Fig. 1. Quarter-section of the complex motion common magnetic circuit electromagnetic converter

Each phase is made of two oppositely disposed coils. The inner part is composed of inner stator with six teeth with tree similar manner winding phases. Inside the stator there is four teeth inner rotor located. Both parts are connected by a common yoke, through which fluxes excited by energized coils close. Common yoke helps to reduce the volume of material. However, it may be a source of both parts influence each other.

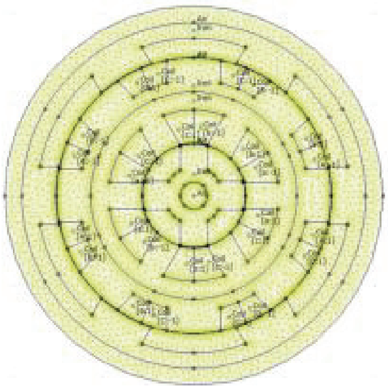

Fig. 2. Radial flux converter model, created in Preprocesor of FEMM 4.2 application

2. Determination of winding inductance

The computational model of converter was made using Matlab and Femm 4.2 software. The script controlling calculations and creating a model in Femm 4.2 was written in Matlab. Calculations were made using the finite element program Femm 4.2.

Winding inductance is one of the most important parameters needed for proper design of power control supply and control strategy. Even more helpful in this target are flux/inductance changes via rotor position waveforms.

In the analyzed case, the inductance of the winding is obtained from flux linkage with winding taken from Femm 4.2 Postprocessor program. Then based on Equations (1) and (2) the winding inductance waveforms were obtained as a function of the angle of rotation of the rotor.

$$\underset{\alpha_{in} \in \left\langle 0, \frac{\tau_{in}}{2} \right\rangle}{\forall} \mathrm{L}_{in} = \mathrm{N}_{in} \frac{\varphi_{in}(\mathrm{i}_{in}, \alpha_{in})}{\mathrm{i}_{in}}, \tag{1}$$

$$\underset{\alpha_{out} \in \left\langle 0, \frac{\tau_{out}}{2} \right\rangle}{\forall} \mathrm{L}_{out} = \mathrm{N}_{out} \frac{\varphi_{out}(\mathrm{i}_{out}, \alpha_{out})}{\mathrm{i}_{out}}, \tag{2}$$

where *N* is number of turns

Figure 4 shows the waveforms as a function of the inductance of the windings of the rotor position. The analysis of changes in the inductance of the outer part winding band shows that for almost 25% of turnover, inductance practically does not change. This is a consequence of sub-optimal height to width ratio of the teeth and is reflected in the course of the torque (Fig. 3).

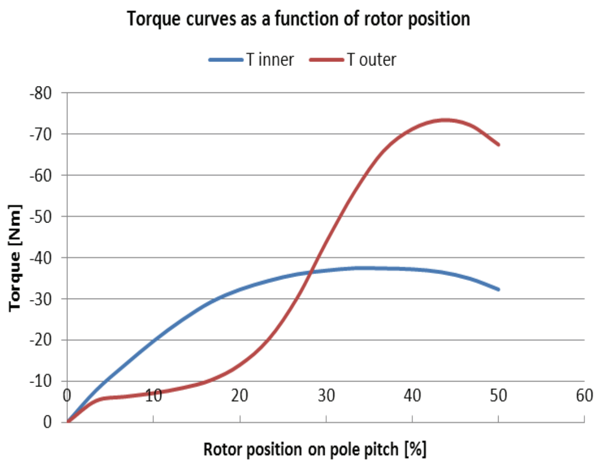

Fig. 3. Torque curves obtained for inner and outer rotor

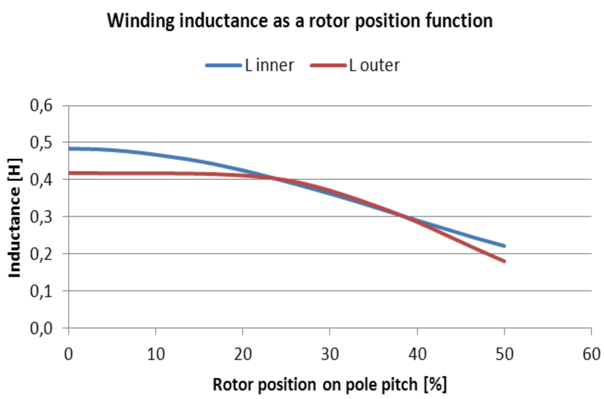

Fig. 4. Inductance curves obtained for inner and outer rotor

Comparing those two waveforms, the inner part torque curve has significantly milder course, the average value slightly lower than the maximum value. The course of the outer part of the torque curve is much worse. Its average value is almost the same, but maximum value is three times higher. The improvement of the structure will be the subject of future research. Different numbers of teeth on the stator and rotor will be examined to obtain good power density and small ripple torque.

3. Study of influence of common magnetic circuit on torque

In Figure 5 a) the flux closing paths, when two circuits are energized can be observed. They differ from those which where only one circuit is supplied (Fig. 5b). Therefore, it is presumed that a common way closing the fluxes can have a negative impact on the operation of the converter. In order to examine this problem closer a study was performed. It was divided into following stages.

Stage 1. For every unique combination of supplying band phases (in normal operation) i.e. in configurations, a + A, a + B, A + C, a + D, all configurations (in 0-τ/2 range) of the rotors position were checked and toque value was recorded.

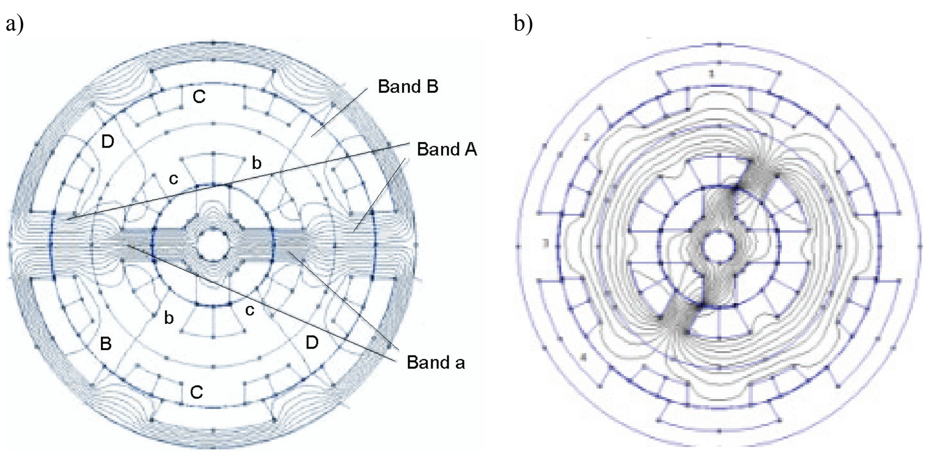

Fig. 5. Distribution of magnetic flux: a) when bands a and A energized, b) when single band energized

Stage 2. Determination of the average torque values at all positions, for four possibility of power supply.

Stage 3. For every unique combination of supplying band phases and all rotor position configurations the relative error of torque were calculated with reference to the average value determined in the Stage 2. The results are shown in Figures 6-13.

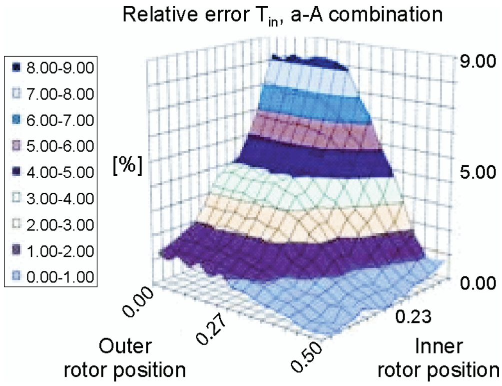

Fig. 6. Distribution of inner torque relative error with a-A combination

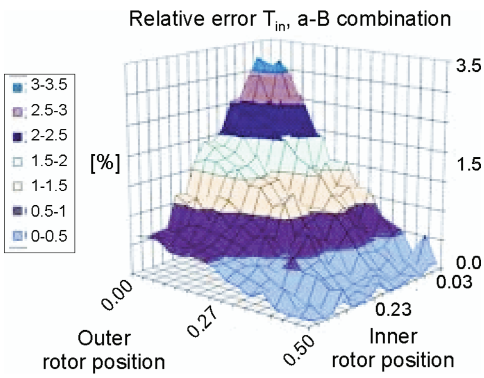

Fig. 7. Distribution of inner torque relative error with a-B combination

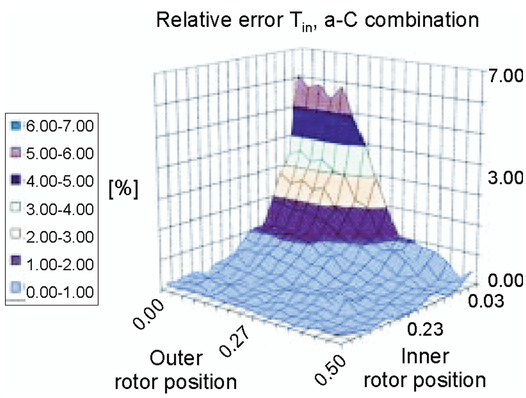

Fig. 8. Distribution of inner torque relative error with a-C combination

Stage 4. For every unique combination of supplying band phases, and rotors positions, in each case the average error value was calculated, and the maximum error value was found. The results are presented in Table 1. Ratio of maximum value to average error value can be defined as torque ripple relative error factor.

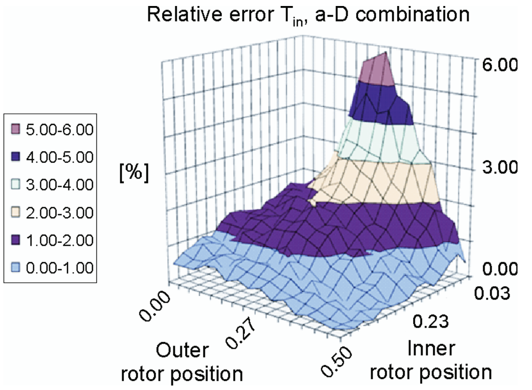

Fig. 9. Distribution of inner torque relative error with a-C combination

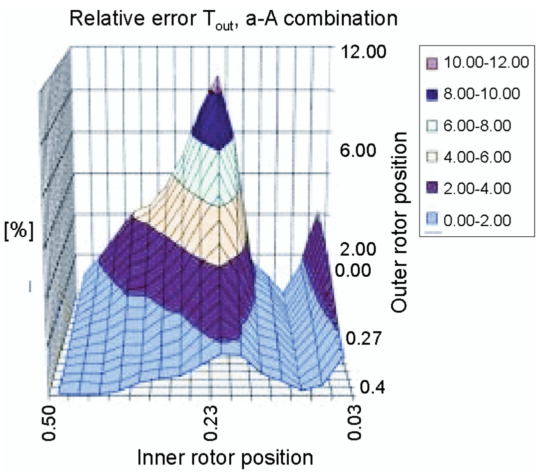

Fig. 10. Distribution of outer torque relative error with a-A combination

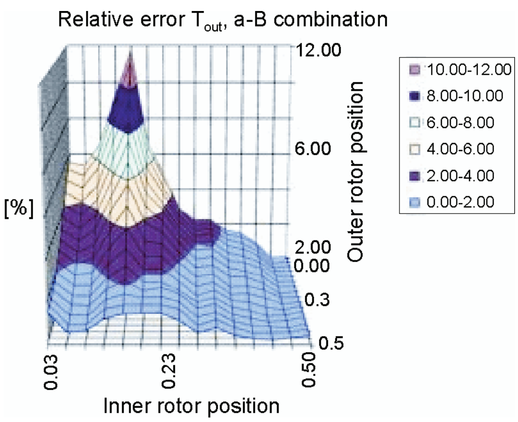

Fig. 11. Distribution of outer torque relative error with a-B combination

Based on carried operations it was possible to compare quantitatively each case. Due to the very small values of torques and large errors values in the start rotors position (i.e. T_{inner} ($\alpha_{inner} = 0$), or $T_{outer}(\alpha_{outer} = 0)$), there were not taken in to account for evaluation.

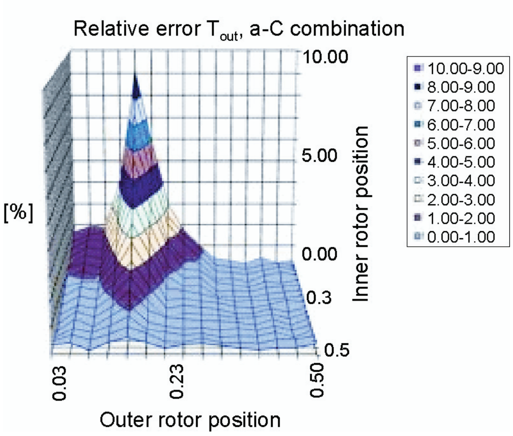

Fig. 12. Distribution of outer torque relative error with a-C combination

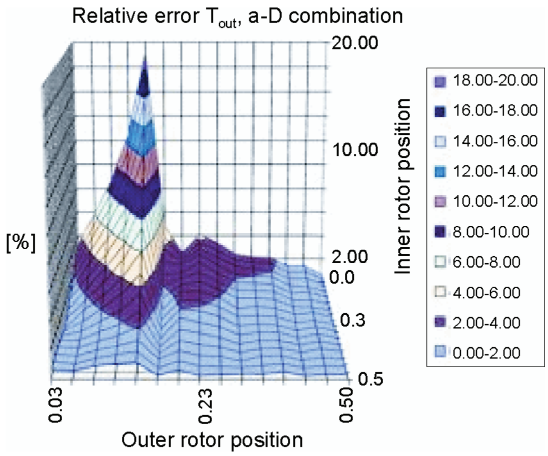

Fig. 13. Distribution of outer torque relative error with a-D combination

Table 1. Results of obtained calculations

No.	Configuration	Maximum relative error value [%]	Average relative error value [%]	Ripple relative error factor
1	dTiaA	8.39	2.40	3.50
2	dTiaB	3.23	0.94	3.44
3	dTiaC	6.08	0.66	9.19
4	dTiaD	5.90	1.31	4.50
5	dToaA	10.64	2.44	4.36
6	dToaB	11.73	0.94	12.48
7	dToaC	9.10	0.94	9.68
8	dToaD	19.13	2.20	8.69

Analyzing the values in Table 1, it can be seen that the least favorable case is where the closest each other bands are energized. It can be seen overall error increase, and abnormal flux closing path, which instead of locking through the stator yoke is closing through the inner rotor. In addition, in almost every case, the largest error for the considering moment occurs when the tooth opposite the rotor is in a position coaxial with the tooth of the supplied tooth of the stator.

4. The study of relative error value as function of current density

The above results were obtained with constant current value. The next step was to check the influence of the current density on torque relative error. For this purpose, another study was performed involving simultaneous turning of two rotors for the same percentage of the pole pitch for different values of current density. For this study configuration a-D was selected. The results are shown in Tables 2-3.

Based on these results it can be seen that with increasing current density also increase torque and relative errors translates into other defined parameters in the preceding paragraphs. This phenomenon is associated with increase of flux density in the common magnetic yoke, and reluctance increase.

Table 2. Results of calculation for inner rotor as a current density function

No.	**Current density [A/m^2]**	**Maximum relative error value [%]**	**Average relative error value (0.06-0.5) [%]**	**Ripple relative error factor**
1	1	1.62	0.92	1.76
2	3	6.32	2.53	2.50
3	5	5.72	3.14	1.82
4	7	6.92	3.51	1.97
5	9	8.15	3.86	2.11
6	11	9.52	4.17	2.28
7	13	10.88	4.51	2.41

Table 3. Results of calculation for outer rotor as a current density function

No.	**Current density [A/m^2]**	**Maximum relative error value [%]**	**Average relative error value (0.06-0.5) [%]**	**Ripple relative error factor**
1	1	1.41	0.88	1.60
2	3	3.68	1.73	2.13
3	5	6.94	3.80	1.82
4	7	11.77	6.19	1.90
5	9	15.99	8.31	1.92
6	11	22.19	10.99	2.02
7	13	31.05	14.00	2.22

5. Conclusions

The research described above is a part of preparations for the formulation of optimization task. On this basis it can be concluded that one of the most important evaluation criteria will be ripple factor. In one scenario, the ripple factor understood as the ratio of the maximum torque value to average value which is used to assess the dynamics of the drive. In the scenario the ripple ratio will be understood as the ratio of the maximum relative error to the average torque relative error. This factor will be used to assess the degree of interaction between the two parts of a common magnetic circuit.

A very important parameter in the design of the electric circuit is the inductance of the winding. It will be the main criterion for determining the motor control strategies and the selection of the number of turns.

On the basis of the relative error calculation can be confirmed by the occurrence moments of the adverse interaction between the inner and outer parts, which increases with increasing current density. The size phenomenon turned out to be at an acceptable level. Next step of work is to find optimal solution for the this phenomenon.

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