DIRECT DRIVE SYSTEM WITH TWO PHASE TRANSVERSE FLUX DISC-TYPE MOTOR

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Abstract: *The permanent magnet transverse flux motor (PMTFM) has an excellent torque to volume ratio compared to any of the conventional motors. The two phase disc rotor PMTFM to be discussed in this paper has a quite simple and robust construction compared with the usual rotating PMTFM. Therefore such a motor can be considered as a competitor for different automotive drives. In the paper two constructive variants are presented and for one of them the design procedure and the performance calculations are carried on by using a coupled analytical and 2D or 3D-FEM computation strategy.*

1. INTRODUCTION

The transverse flux (TF) machine was proposed and named by Weh in the late 80's [1] and several variants were designed and prototyped by now [2], [3]. The claw pole flux pattern implies the transverse flux concept, but the TF machine has enlarged this concept by its very dedicated topology, which includes usually the flux concentration principle for the permanent magnets (PMs) excited structures. Characteristic for all types of TF machines is the presence of the transverse flux paths and of the homopolar MMF produced by a ring coil in which the current flows parallel to the direction of rotation, [1] - [5].

The TF machine variants, with a disc-type configuration proposed in [4], [5] differs in principia, but have a common point, a much simpler construction. Both of them employ permanent magnets (PMs) on the rotor and a coil type winding on the stator. The structure proposed in [4] does not imply the flux concentration and that was the main reason, which conducted to not so good characteristics.

The structure proposed in this paper is based on the rotor flux concentrating pattern and the expected characteristics should be better than for the previously discussed TF machine.

Basic design-estimation procedure for a radial flux permanent magnet transverse flux motor (PMTFM) was presented in [3], [6] and the differences for an axial flux PMTFM design-estimation was discussed briefly in [5]. A mathematical model of the TFM is presented in [7]. A basic view on the way the numerical models, finite element method (FEM) included, can be employed in the PMTFM design is given in [8].

The automotive application, which is considered here, requires, besides a very large torque to volume ratio, constructive simplicity and good reliability. Consequently the proposed PMTFM structure a two phase stator and one has active rotor in an axial flux pattern, Fig. 1.

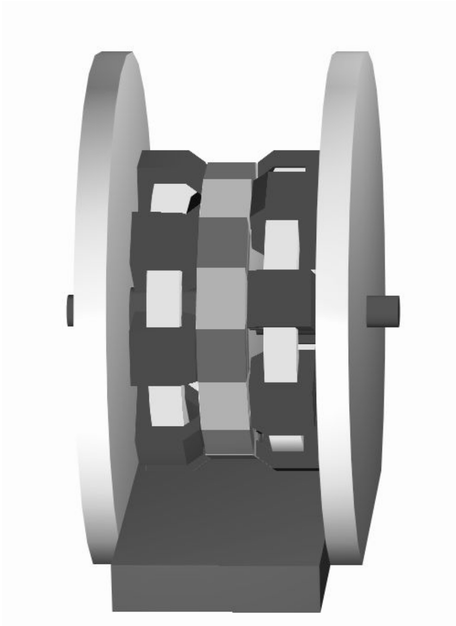


Figure 1. General view of the two-phase TF machine

The two phase stator has the poles in quadrature, while the rotor, with a flux concentrating topology, is common for both stator phases, Fig. 2. There are two possible constructive variants with pulse voltage supply, respectively with sinusoidal voltage supply, as shown lately in the paper.

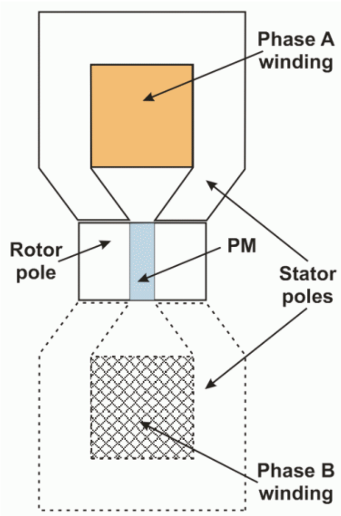


Figure 2. Stator poles and rotor structure

The machine structure uses a modular concept. Each pole is constructed individually, thus, the number and the position of poles can be modified. The winding is concentric, like a torus. The rotor core has a flux concentrating capability with a variable magnet area, so the air-gap flux density can be adjusted independently of the rotor radius.

The stator and the rotor cores are made of pre-cut transformer type silicon steel sheets and the magnets (NdFeB) have very good performances (H_c = 930 kA/m, B_r = 1.21 T). The cross section of a stator and a rotor pole is illustrated in Fig. 2. Each rotor pole is constructed from two identical core stacks with PM inserted in between. The rotor poles are attached to a nonmagnetic disk that holds the rotor cores. In Fig. 3 a view of the disc rotor with alternative polarity PMs is given.

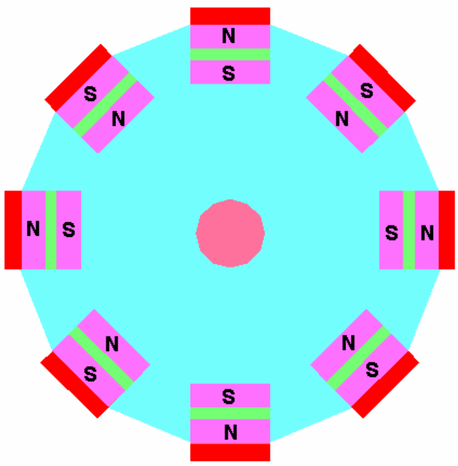


Figure 3. View of the disc rotor with alternate polarity PMs

The shaft is attached to the disk to rotate the rotor. The stator consists of two sides, Figs. 1 and 2, one for each phase. The poles on each side are attached to a plate which holds the stator poles. The stator winding between the stator poles is exposed to open air, which assures a better cooling.

In the paper, two possible constructive variants are discussed, one with unipolar pulse voltage supply, the other with sinusoidal voltage supply. A sizing-dimensioning procedure, adapted for such a structure, was carried out and, the motor's characteristics were computed based on the analytical and 2D or 3D finite element method (FEM) field analysis.

The calculated results clearly show that the two-phase proposed PMTFM, in both discussed variants, offers a valuable solution for the special drive application considered.

2. CONSTRUCTIVE VARIANTS, SUPPLY AND CONTROL

The option for the actual structure is due mostly to its large torque to volume ratio, constructive simplicity and good performances. The two constructive variants considered with unipolar pulse voltage supply and with sinusoidal voltage supply respectively have quite the same basic construction. It means that in both cases the disc rotor pole's pieces are common for both stators which are placed on the rotor opposite sides. The main difference consists in the number of stator poles, but the rotor PMs are placed in different manner, too. In the first case, the UP variant, each stator has the same number of poles as the rotor whose PMs are polarised all in the same manner, Fig. 4.

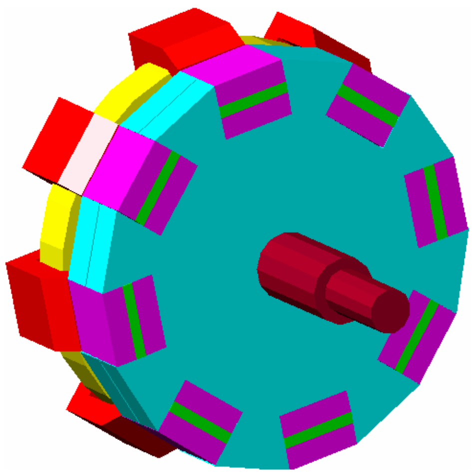


Figure 4. A partial view of the axial field PMTFM, UP variant

In the AP variant case each stator has half of the rotor pole numbers, Fig. 5, and the rotor has the PMs with alternate polarity, Fig. 3. In both variants the stator and rotor pole length is equal and the same.

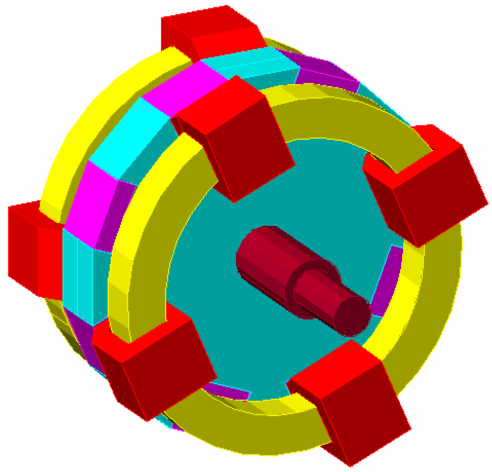


Figure 5. A partial view of the axial field PMTFM, AP variant

In Fig. 6 the main dimensions of the stator and rotor poles are given. As settled before, the poles have identical dimensions in both variants.

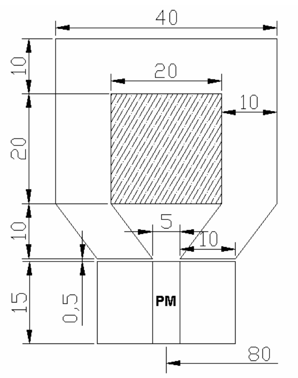


Figure 6. Stator and rotor pole dimensions

The UP variant, with the same number of poles on rotor and both stator sides, has quite a clear status and does not imply anything special. The AP variant, Fig. 5, with its non-uniformly distributed stator poles, offers the advantage of a sinusoidal voltage supply. In Fig. 7 successive rotor positions against stator poles are presented. In a stator axis the air-gap flux density variation is given, in a simplified manner, in Fig. 8.

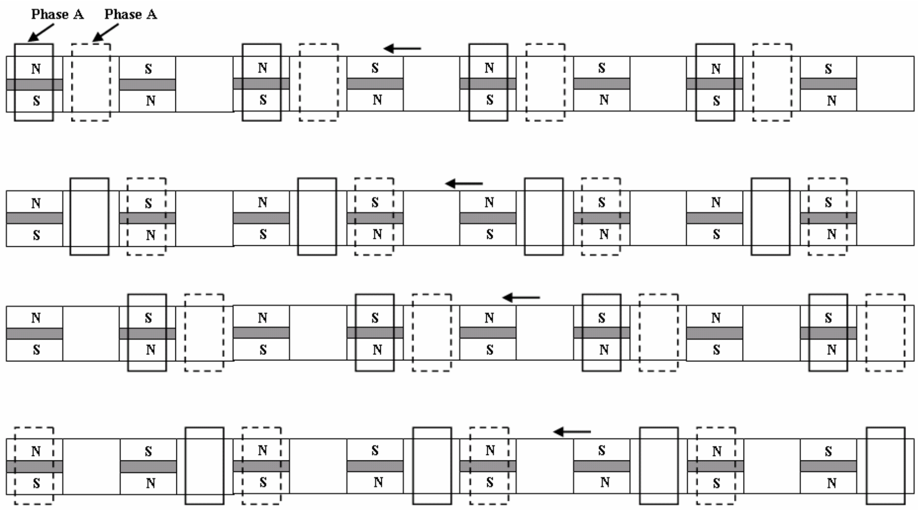
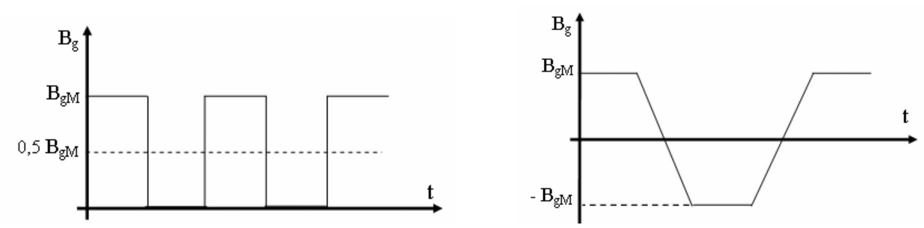


Figure 7. Successive rotor positions against stator poles, AP variant



a) Rotor PMs with the same polarity b) Rotor PMs with alternate polarity

Figure 8. Simplified air-gap flux density variation in a stator pole axis

It is quite clear that in the AP variant the stator and the rotor number of poles should be increased in order to obtain a larger value for the stator phase induced emf. One must consider the fact that by increasing the number of rotor poles the PM's volume is increased, too, and so is the motor cost. Therefore such an option should be carefully evaluated and adopted only if the output torque increases justify the extra cost. It was not our intention to develop here a study on this subject and to offer some solutions, it is the object of a paper which will follow this year. Anyway, by calculating the main harmonic amplitude the results are:

$$B_{gM(1)UP} = 0.5 \cdot B_{gM} \cdot 0.64 \cdot T \quad (1)$$

$$B_{gM(1)AP} = B_{gM} \cdot 1.15 \cdot T \quad (2)$$

where the maximum actual amplitude of the air-gap flux density B_{gM} was considered the same.

Obviously the above given values are calculated considering only the PM's mmf, which means a no-load operating for PMTFM. Considering that the number of turns is the same in both variants then the induced emf values, computed by Faraday's law,

$$e = -N \frac{d\Phi}{dt} \quad (3)$$

are:

$$E_{MUP} = N \cdot 2\pi \cdot n \cdot p \cdot A_p \cdot 0.32 \cdot B_{gM} \quad (4)$$

$$E_{MAP} = N \cdot 2\pi \cdot n \cdot p^* \cdot A_p \cdot 1.15 \cdot B_{gM} \quad (5)$$

and even if $p^* = p/2$, the maximum induced emf in the AP variant is almost double to the maximum induced emf in the UP variant, which is quite favourable.

3. RESULTS AND CONCLUSIONS

It is discussed here a PMTFM designed in AP variant, with four pole pair, Figs. 3 and 5. in the design stage a sizing-estimation procedure was developed and consequently applied and a 2D-FEM analysis assures some complementary calculations and an important check up concerning the PM's operating point.

The main dimensions are given in Fig. 6 and due to pole length the pole area results $A_p = 345.8\times10^{-6}$ m^2. Considering the air-gap diameter, which is $D_g = 0.16$ m, the small number of poles and the reduced active volume of the motor the expected output power was somewhere around 900 W.

The stator current density was adopted $J = 4$ A/mm^2, even it could be larger, to avoid any problems concerning the PM's temperature over-increase. With a slot fill factor $k_{fill} = 0.5$ and a slot area $A_{sl} = 400$ mm^2 resulted a stator phase current $I = 16$ A. The input voltage adopted is $V_1 = 45$ V and consequently the input power is:

$$S_1 = 2 \cdot 45 \cdot 16 = 1440 \text{ VA} \quad (6)$$

For such a low power motor the efficiency and the power factor should be $\eta = 0.88$, $\cos\varphi = 0.65$ and the rated output power resulted:

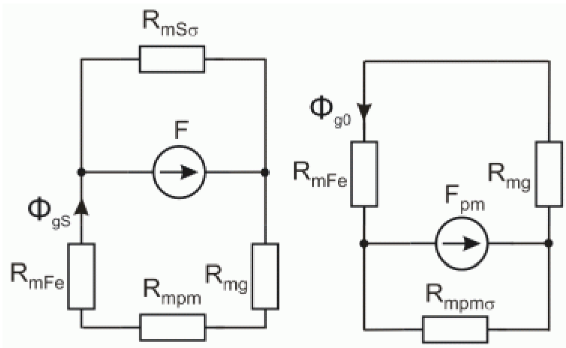
$$P_2 = S_1 \cdot \cos\phi \cdot \eta = 824 \text{ W} \quad (7)$$

which is near by the initial estimation.

The no-load air-gap flux density, with the stator and rotor pole in aligned position, is obtained via a 2D-FEM calculation [5], $B_{g0} = 1.2$ T and consequently the polar flux produced by the PM's mmf results:

$$\Phi_{gs} = B_{g0} \cdot A_P = 0.415 \cdot 10^{-3} \text{ Vs} \quad (8)$$

the no-load air-gap flux can be computed by employing the magnetic equivalent circuit given in Fig. 9a, where the leakage coefficient k_σ, computed via a 2D-FEM analysis [5] is 0.0265. The air-gap flux produced by the stator phase mmf with the poles in aligned position can be computed by using the magnetic equivalent circuit given in Fig. 9b. The stator phase leakage magnetic reluctance can be computed in an usual manner, as for a rotating PMTFM [3].



a) stator reaction flux b) no-load flux

Figure 9. Magnetic equivalent circuit

The maximum phase induced emf is:

$$E_M = N \cdot \Phi_{g0} \cdot 2\pi \cdot n \cdot p^2 = 41.7 \text{ V} \quad (9)$$

and the phase inductance results

$$L_s = N \cdot p \cdot \frac{\Phi_{g0}}{I_{max}} = 3.668 \cdot 10^{-3} \text{ H} \quad (10)$$

where the turn number is $N = 50$.

If the stator current is oriented on the q-axis, then the power factor results [6] $\cos\varphi = 0.668$, a value a bit larger than the initial adopted one.

The torque per pole pair and phase is [6]:

$$T_{pp} = N \cdot p \cdot I_M \cdot \Phi_{g0} = 1.88 \text{ Nm} \qquad (11)$$

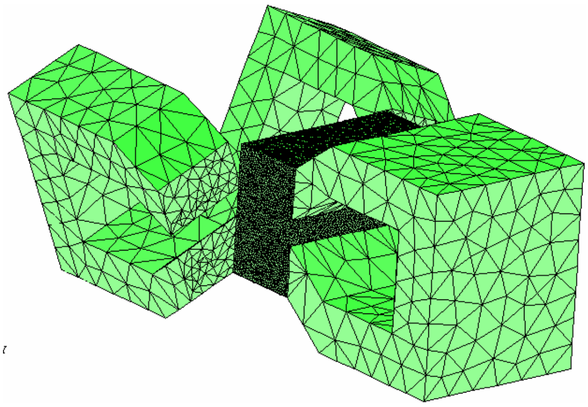
and consequently the total output torque results:

$$T_2 = 2 \cdot 4 \cdot 0.5 \cdot 1.8 = 7.52 \text{ Nm} \qquad (12)$$

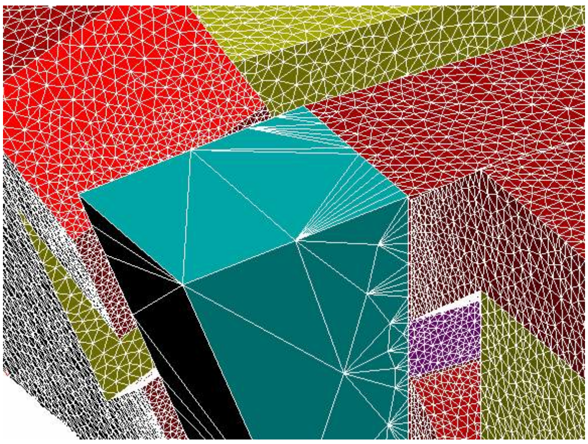
which corresponds to a rated output power of P_2 = 945 W for a rated speed n = 1200 rpm.

It is obvious that the power factor increases if the stator current has a d-axis component, but decreases the developed torque and power for the same phase current.

Anyway, as proved through a 3D-FEM computation, the 3D mesh for the UP variant being given in Fig. 10, the power factor cannot be increased that much due to the large leakages existing in the stator homopolar structure.



a) full view



b) detailed view

Figure 10. 3D-FEM mesh for stator and rotor core, a symmetrical part

In the UP variant case the symmetry basic element is given in Fig. 11.

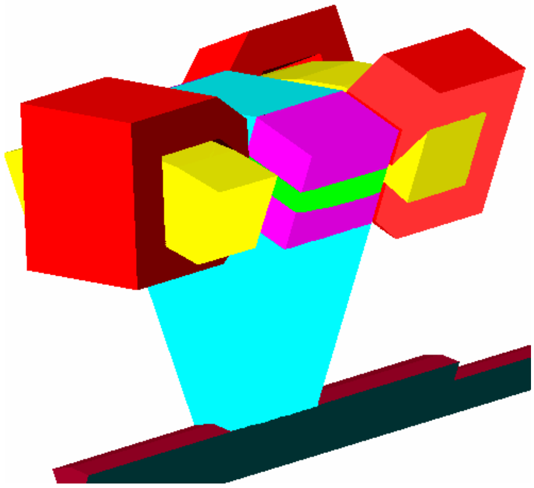


Figure 11. A portion of the two-phase PMFEM, UP variant, obtained through a symmetrical procedure

To check the PM's operating point in order to avoid the PM's demagnetisation due to the stator reaction mmf a 2D-FEM analysis was used, the resulting B_{pm}=f(I) characteristic for an aligned position being given in Fig. 12..

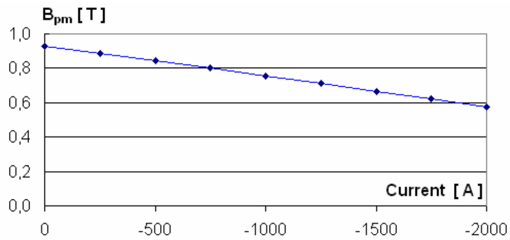


Figure 12. Flux density versus current, stator flux opposes to the PM's flux

As one can see the PM's demagnetisation is avoided up to a stator current value larger than the double rated value. In Fig. 12 the current on the horizontal scale is the total current, in fact the mmf produced by the stator phase.

The proposed two-phase PMTFM has a large starting torque, larger than the rated one, which is favourable for the considered application.

The proposed structure has a quite good torque to volume ratio and an important simplicity concerning its construction. The resulted performances are quite closed to the performances obtained for the rotating PMTFM and due to its simplicity the two phase disc rotor PMTFM is well suited to the specific application considered.

It must be pointed out that the coupled analytical and 2D or 3D-FEM performance calculation carried on in this case gave quite accurate results and it can be extended to some other similar cases.

4. ACKNOWLEDGEMENT

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