TRANSVERSE-FLUX PERMANENT MAGNET (TFPM) MACHINE WITH TOOTHED ROTOR

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Abstract – The geometry of the Transverse Flux Permanent Magnet machine with Toothed Rotor is derived. This new machine geometry allows easy production and low mass of active material. Experiments on a linear actuator are presented in the paper.

INTRODUCTION

The principle of Transverse-Flux Permanent Magnet (TFPM) machines has been discussed in a number of publications by Weh and May (1), Henneberger and Bork (2), Maddison et al (3) and others. The few TFPM machines built mostly find their applications where high torque and low-to-medium rotational speed are required. The low mass of active material for a given torque makes TFPM machines an attractive solution in direct-drive applications, in replacement of the usual combination of gearbox and induction machine. Such direct-drive applications are generators for wind turbines, traction motors for busses and trains, propulsion motors for ships, etc. Although it is an important factor, active material is not the only component in the total machine cost. If cost-competitiveness is an issue, not only TFPM machines must have a low mass of active material, but also must they be easy to produce.

Two main families of TFPM machines have emerged until now: the TFPM machines with surface magnets described by (2) and by Harris and Mecrow (4), and the TFPM machines with flux-concentration described by Weh (5), Maddison et al (3), Mecrow et al (6) and others. Although the TFPM machines with surface magnets showed a certain ease of construction, it has been discussed by Harris et al (7) that they give lower performances than the TFPM machines with flux-concentration. If low mass of active material is targeted, TFPM machines with flux-concentration should preferably be used. However, the TFPM machines with flux-concentration, which were presented in the past are either difficult to build, or make a massive use of powdered-iron material in their stator cores.

It should be noted that in both families of TFPM machines, the production of windings is tremendously simpler than for an induction machine. This is a substantial advantage of TFPM machines.

In this paper, a new TFPM machine with Toothed Rotor is derived, with the following constraints:

- easy rotor construction;
- permanent magnets in flux concentration;
- stator cores with laminated steel.

In the next section, the new topology of TFPM with Toothed Rotor is derived step-by-step, by using the TFPM machine studied by Weh (5) as a starting point. Then experiments on a linear version of this geometry are presented. These experimental results are also compared with the results of finite element simulations. In the last part of the paper, the expected performance of a rotary version of this machine is compared to the performance of a RFPM machine.

DERIVATION OF THE TFPM MACHINE WITH TOOTHED ROTOR

A new TFPM structure will be derived. The machine geometry proposed by (5) is used as a starting point, and illustrated in fig.1.

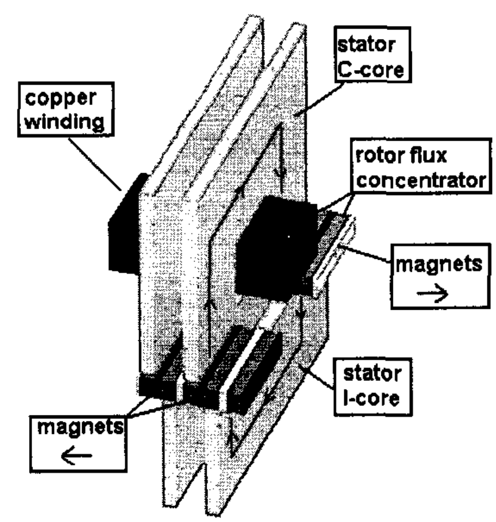

Fig. 1: TFPM structure with flux-concentration proposed by Weh (5). Four (4) poles of a linear version of this structure are shown.

This structure uses permanent magnets in flux concentration, which exhibits a high ratio of torque per mass of active material. In addition, the TFPM structure of fig. 1 allows laminated steel to be used in the stator parts, due to the planar flux circulation. Laminated steel gives better performances than powdered iron, as shown in table 1.

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TABLE 1: Magnetic properties of powdered iron ATOMET–EM1 (8) and laminated steel M-45 (9)

	Powdered iron	Laminated steel 0.35 mm
Initial relative DC permeability	290	2000
Saturation flux density	1.4 T	1.9 T
Iron losses @ 1.0T/400 Hz	77 W/kg	11 W/kg

A very important point is the iron losses, which are about seven (7) times lower in 0.35-mm thick laminated electric steel at 400 Hz. This point is of utmost importance in TFPM machines, where pole pitches are short and consequently electrical frequencies are rather high.

Production of flux–concentrating TFPM machines

Different authors have emphasized the advantages of TFPM machines, but also the difficulties of building them. If TFPM machines are to be produced in large quantities, the manufacturing process should be carefully investigated.

As mentioned in the introduction, the stator winding of TFPM machines is very simple. However, other parts of the TFPM machine of fig. 1 present important production difficulties. Some of these problems are:

- presence of a double-sided stator;
- dependence of each magnet location on the total build-up of mechanical tolerances due to the other rotor pieces
- manual placement of the rotor magnets and flux concentrators

These three (3) points are here further discussed.

Double-sided stator – The double-sided stator arrangement of fig.1 provides very little space for mechanically retaining the magnets and flux concentrators to the rotor. The only possibility is to fix each flux concentrator to a rotor disk on one side, by means of a screw or by gluing the flux concentrators to that rotor disk. From the production point of view, this is a rather difficult concept. Also, the double-sided stator will give rise to some difficulties during insertion of the rotor in between the two rows of stator cores. Although many schemes can be imagined, it is very unlikely that the magnets and flux concentrators can be retained by both sides during insertion.

Another point concerning the double-sided stator is the inherent low mechanical stiffness, due to the presence of two rows of magnets and flux concentrators. Each row can only be retained from one side, and must be mechanically joined together in the central part. The attachment of the two rows of magnets together is a difficulty which can hardly be overcome in an elegant manner, and which leads to a weaker machine construction.

A last point concerning the double-sided stator is the presence of two (2) clearance air gaps radially on either side of the rotor. This complicates the mechanical design, with an additional requirement of very low thermal expansion or contraction in the radial direction. The expansion and contraction of both rotor and stator must be thoroughly equal in the radial direction, in order to avoid the rotor from touching the stator on one of the two sides. The double-sided air gap also requires lower mechanical tolerances in the radial direction, when manufacturing all the parts.

Mechanical circumferential tolerances in the rotor – All TFPM machines with flux-concentration described in the scientific literature have one or two rows of a circular arrangement of magnets and flux concentrators, stacked one next to the other as shown in fig. 2.

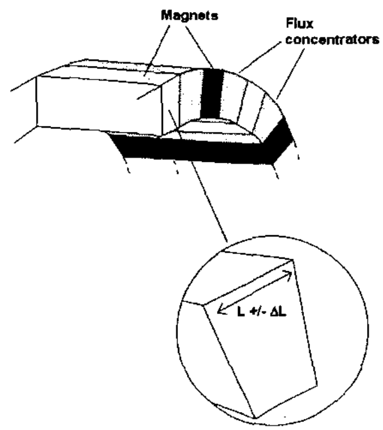


Fig. 2: Stacking of permanent magnets and flux concentrators in most TFPM structures with flux concentration.

Normally, the pieces of fig. 2 are fixed one to the other with glue. Unfortunately, there are intrinsic mechanical tolerances in the circumferential direction, related to the manufacturing of either the magnets or the flux concentrators. These tolerances add up in the arrangement of fig. 2, making the exact location of each piece of magnet or flux concentrator dependent upon the sum of the mechanical tolerances caused by all the other pieces in the ring. Of course, it is possible that such tolerances cancel one another, but this may not necessarily be the case. This difficulty is also pointed out by Blissenbach et al (10).

Manual placement of rotor pieces – The construction of a rotor ring, as the one shown in fig. 2 is a time-consuming task. The presence of attracting and repulsive forces between magnetized pieces and flux concentrators along with the use of glue to fix the pieces together require softness, precision and adjustment. It is very unlikely that a machine can perform this operation without human intervention. This is especially true, when it comes to closing the ring on itself, where very little space becomes available between the two ends of the rings. Then it will become very difficult for a tool or a machine to work in that area.

TFPM machine with Toothed Rotor

In order to overcome the difficulties mentioned in the last paragraphs, a new TFPM machine topology is derived. Starting from fig. 1, the double-sided stator is made single-sided, by moving the lower stator cores to the upper side. This first step is shown in fig. 3.

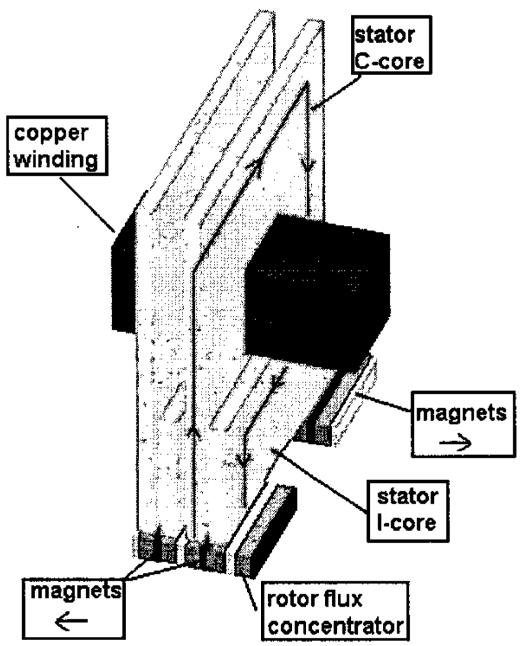


Fig. 3: (Step 1): Single-stator version of fig. 1

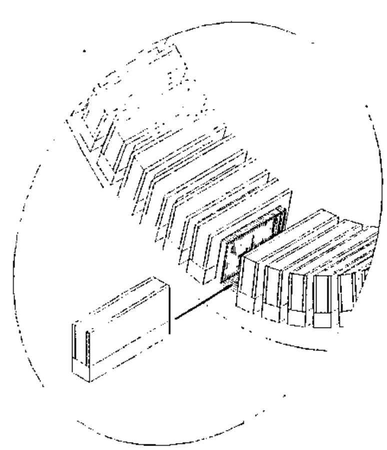


Fig. 4: Introduction of a toothed rotor structure

The next step is the addition of a guiding structure to the rotor. The guiding structure solves both the problems of the circumferential mechanical tolerances, and automation of the rotor production process. This guiding structure is built from a stack of toothed laminations in the rotor, as shown in fig. 4.

Each magnet piece of fig. 3 can be cut in two magnets with the same direction of magnetization. These two magnets with identical directions of magnetization are placed on each side of the tooth, as shown in fig. 5.

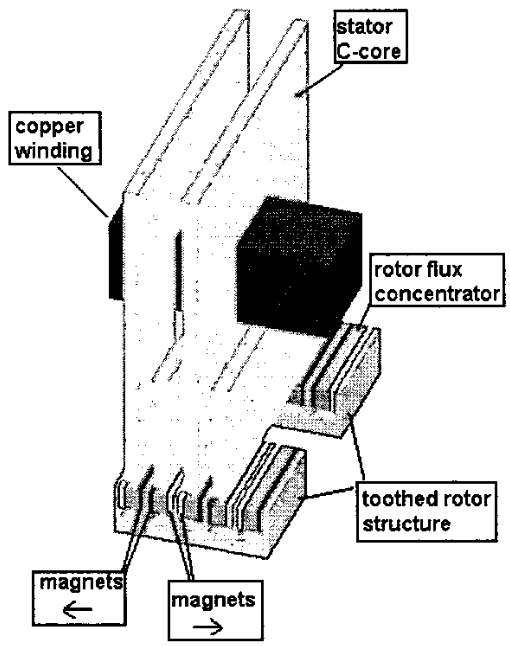


Fig. 5: (Step 2): insertion of the toothed rotor to fig. 3

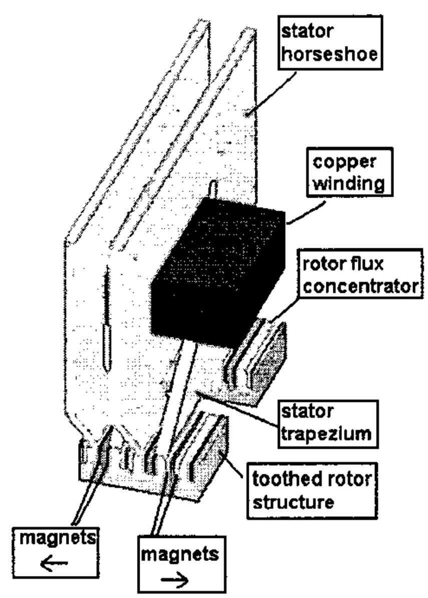


Fig. 6: (Step 3): Reduction of stator leakage by using a stator horseshoe and a trapezoidal flux return.

One of the main problems in single-sided TFPM stators is the stator leakage flux between the stator C-core part of fig. 5, and the I-core. This can be partly overcome, by forming the I-core into a trapezium, and by shaping the C-core into a horseshoe with a foot, as shown in fig. 6. This reduces the area of flux leakage between the two stator cores.

The insertion of the toothed structure has formed an additional leakage path between the stator horseshoe and the trapezoidal flux return. The performance of the machine of fig. 6 can be further increased, by slightly reducing the rotor tooth height. A factor 3-4 between the clearance air gap and the stator-tooth distance is generally sufficient to reduce the tooth leakage flux to negligible levels. The reduction of the rotor teeth height is shown in fig.7.

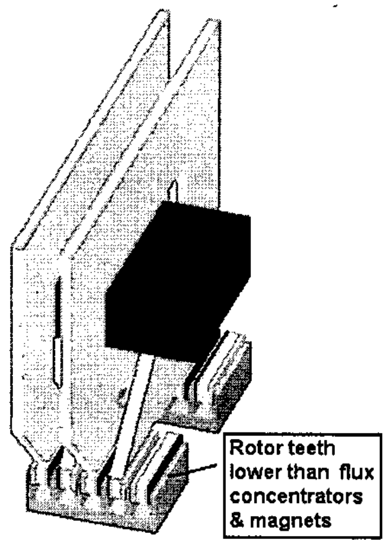


Fig.7: (Step 4): Reduction of the rotor teeth height

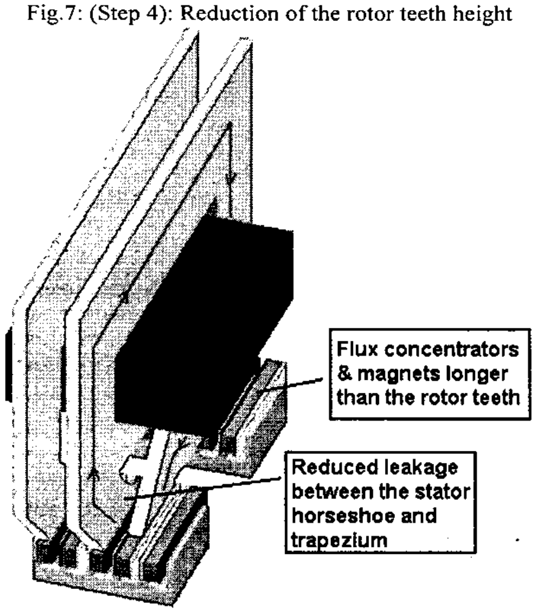


Fig.8: Final result: TFPM machine with Toothed Rotor.

The stator leakage flux can be reduced further, if the flux concentrators and magnets are made slightly longer than the rotor stack, as shown in fig.8. The stator horseshoe is made a little longer, thus reducing further the leakage area between the stator horseshoe and the stator trapezium. In that case, the flux concentrators are also used to carry the flux in the axial direction. This final step is shown in fig. 8 and fig. 9, which display the TFPM machine with Toothed Rotor proposed in this paper.

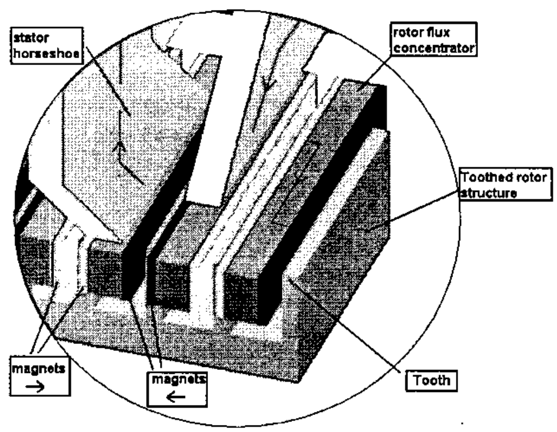


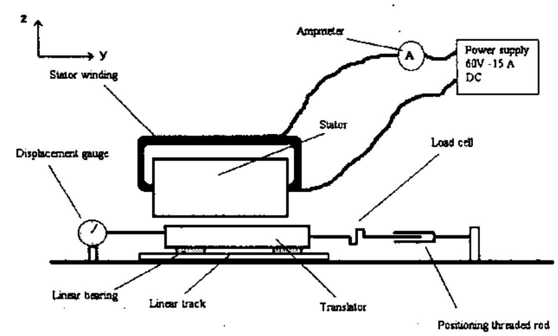
Fig.9: Close-up on the TFPM machine with Toothed Rotor

Shortcomings related to the toothed rotor – Although many advantages result from the use of a toothed rotor from a construction point of view, one main shortcoming is identified. For structural requirements, the teeth used in the rotor have a minimum width of 2 – 4 mm. This additional width increases slightly the pole pitch, and reduces the number of poles available in the total circumference. This reduces the total tangential force, and gives a lower torque, compared to the machine structure of fig. 1. This is the price to pay for a toothed rotor.

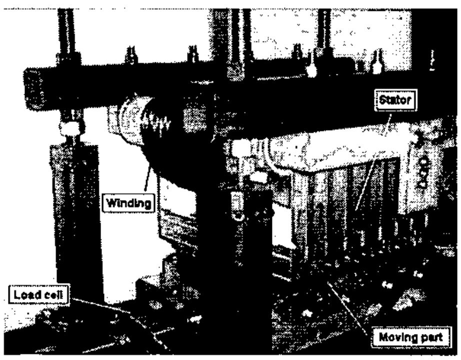
Even with this disadvantage being considered, the TFPM machine with Toothed Rotor provides a much higher value of torque/mass than the RFPM machine, as it will be discussed further in the paper.

EXPERIMENTS ON A LINEAR TFPM ACTUATOR WITH TOOTHED ROTOR

A linear actuator was built with the TFPM geometry with Toothed Rotor of fig. 8. The experimental set-up used is shown in fig. 10. The materials used for the construction were NdFeB for the magnets, M-45 electric steel with 0.35 mm thickness for the stator horseshoes and trapeziums, and ATOMET-EM1 powdered iron for the flux concentrators.



a)



b)

Fig. 10 Linear actuator using the TFPM structure with Toothed Rotor. a) test set-up b) picture

The dimensions of the linear actuator are given in table 2. It must be noted that the dimensions of this linear actuator have not been optimized. The purpose of this actuator was only to demonstrate the ability of the TFPM machine with Toothed Rotor to generate force. The linear actuator was operated in a static way, and

TABLE 2: Main parameters of the linear TFPM actuator with Toothed Rotor built. (x, y, z coordinate system refers to fig. 10 a))

Pole pitch (y – axis)	16 mm
Number of poles	16
Number of turns in the stator winding	538
Magnet thickness (y – axis)	2 mm
Length of magnets - flux concentrators (x – axis)	72 mm
Width of magnets – flux concentrators (z – axis)	12 mm
Thickness of flux concentrators (y – axis)	8 mm
Rotor tooth width (y-axis)	4 mm
Rotor tooth width (x – axis)	48 mm
Slot depth (z-axis)	14 mm
Air gap (z-axis)	1 mm
Stator – Tooth distance (z-axis)	4 mm
Stator core thickness (y-axis)	8 mm
Length of the stator core foot (x-axis)	42 mm

only the static forces have been recorded. Fig. 11 shows the forces measured as a function of the translator position for a constant current of 2.5 A.

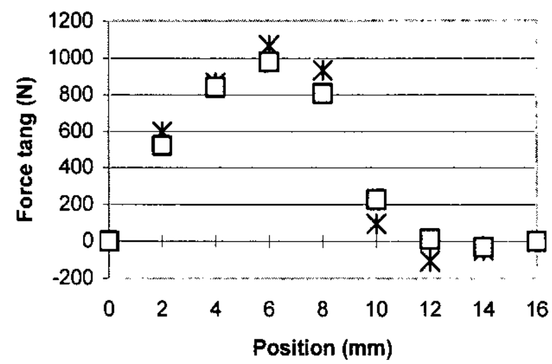


Fig. 11: Static force versus position, for i = 2.5 A, and number of turns = 538. Stars = Finite Element calculations; squares = measured.

The results of fig. 11 show a good correlation between the force values measured, and those predicted with the finite element analysis computation. We can conclude that the TFPM structure with Toothed Rotor proves its ability to generate tangential forces.

Problems encountered during construction

One of the targets in developing the TFPM machine with Toothed Rotor is to simplify the production process of flux-concentrating TFPM machines. During the construction phase of the linear actuator, the different production advantages described earlier in this paper could successfully be tested. The sub-assembly composed of one flux concentrator and two magnets could easily be mounted. The magnets were glued to the concentrators, and each concentrator was glued to an aluminum block. The aluminum block is necessary to keep the magnet field from leaking into the bottom of the slot, and is also used to retain the concentrator to the toothed rotor structure. The sub-assembly formed by the magnets, the flux concentrator and the aluminum block was then inserted into the toothed structure. For the linear actuator, this whole process was done manually, but could easily be automated.

The main problem encountered was the weak mechanical bonding between the flux concentrator and the aluminum block, which could be solved by proper selection of the glue type.

Another point concerns the production of the flux-concentrators. Laminated steel M-45 was first used for this purpose, by stacking and welding them together. In a second step, this production process was substantially improved by making the flux concentrators from molded powdered-iron. The static forces obtained were also slightly higher with powdered-iron.

DESIGN PERFORMANCE OF A ROTATING MACHINE

The next step into the investigation of the TFPM machine with Toothed Rotor is the construction of a rotating electrical machine. At this point, this rotating machine has not yet been built. However, the design specifications and the expected performance have been established as follows: outside diameter = 0.55 m, pole pitch = 14 mm, tooth width = 4 mm, number of poles = 104, number of phases = 3, nominal rotational speed = 100 rpm, axial length = 62 cm, mass of active material = 252 kg, nominal torque = 3200 Nm, mechanical power = 33 kW, efficiency at full-load = 95%, air gap = 1 mm. This gives a torque/mass of 12 Nm/kg. It must be noted that the active material considered here is: permanent magnets, flux concentrators, rotor teeth, stator horseshoes, stator trapeziums and copper windings.

By comparison, a three-phase RFPM machine having the same outside diameter, torque rating, air gap and efficiency would yield the following characteristics, when optimized for high torque/mass: total axial length (including windings) = 76 cm, active mass = 602 kg. Such a RFPM machine would yield a torque/mass = 5.3 Nm/kg. These numbers show a factor 2.3 between the torque/mass of the TFPM machine with Toothed Rotor over the RFPM machine. In this comparison, it must be noted that efficiency is a key factor. If an efficiency of 90% is targeted, the torque/mass of the two machine types can be increased respectively to 23 Nm/kg and 9 Nm/kg, if the same diameter is used.

CONCLUSION

A new machine topology was derived, which makes use of the Transverse-Flux principle with permanent magnets in flux concentration. The new TFPM machine with Toothed Rotor has a single-sided stator, and a rotor with teeth. In the toothed rotor arrangement, the location of magnet pieces and flux concentrators is independent from the mechanical tolerances obtained in the neighboring rotor magnets and concentrators. Also, the subassembly composed of one flux concentrator, two magnets and one insulating block can be easily inserted and extracted independently from the other pieces. This process could be easily automated. A prototype of the TFPM structure with Toothed Rotor was built in the form of a linear actuator, and the force production capability of the concept could be verified.

In a TFPM rotating machine with Toothed Rotor, the torque/mass is expected to be more than 2 times higher than the torque/mass of the RFPM machine design, if active material is considered. The advantage factor could be increased if a tooth width narrower than 4 mm can be used in the rotor structure of the TFPM machine with Toothed Rotor.

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The concept of TFPM machine with Toothed Rotor is protected by an international patent application.

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