

Study of TFPM machines with toothed rotor applied to direct-drive generators for wind turbines

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Abstract—Today, the combination gearbox-medium-speed (1000-2000 rpm) induction generator dominates the market of MW-scale wind turbines. This is due to the lower costs of the gearbox option compared to the costs of gearless systems. Various Transverse-Flux Permanent Magnet (TFPM) machine topologies are investigated for cost reduction. TFPM machines with toothed rotor are compared with the conventional PM synchronous machines based on their optimized cost/torque. The TFPM machine with toothed rotor obtains lower cost/torque for diameters of 0.5 m and 1.0 m. At diameters larger than 1.0 m, the conventional PM synchronous machine obtains lower cost/torque.

Index Terms—Wind Turbines, Direct-Drive, Transverse-Flux PM machines.

I. INTRODUCTION

DIRECT-DRIVE wind turbines have no gearbox. Therefore, the following advantages can be claimed:

- avoided costs of the gearbox;
- no maintenance related to the replacement of oil;
- less bearings, reducing the maintenance related to the greasing of the bearings;
- less moving parts, leading to increased reliability;
- no contacts between gears, leading to increased reliability;
- reduction of acoustical noise and vibrations;
- avoided friction losses of the gearbox.

However, the lower rotational speed of the direct-drive generator leads to a high torque rating, which demands a synchronous generator. Induction generator used as direct-drive generators would be too bulky. The presence of a high-torque rating on the synchronous generator has the following drawbacks:

- increased generator mass, size and costs;

-- requires a power electronics converter, rated 100% of the nominal power, with its related cost and losses.

Among all the advantages and drawbacks listed above, the difference in capital cost between the direct-drive generator/converter combination and the gearbox/induction machine/converter of the doubly-fed system is probably the most important criterium in the decision-making process. At this moment, there is a general trend in the wind turbine industry towards the use of doubly-fed systems with gearbox, due to the high cost of the direct-drive synchronous generator.

A few authors [1]-[3] have investigated the costs of permanent magnet and wound-rotor synchronous generators for this application. Also, in a previous NORPIE communication [4], a literature survey was presented by the authors, which included a large number of prototypes and designs of a wide variety of PM topologies. The results of that study suggested that TFPM machine geometries could substantially reduce the cost of the machine active material for a given torque value compared to more conventional PM machine topologies. In principle, the TFPM machine has the potential for very high current loading, leading to very high force densities. For example, current loadings of 300 kA/m and force densities of 150 kN/m² are possible for TFPM machines [5]. This is indeed much higher than for conventional PM synchronous machines. TFPM machines can have both very short pole pitch and large winding window area, while conventional synchronous machines suffer from a decreasing copper cross-section as the pole pitch decreases.

To assess the true potential of TFPM machines for cost reduction, it is clear that the literature survey presented in [4] is insufficient. In the latter publication, each machine design has a different operating condition and it is not clear whether the resulting machines are designed with the same levels of optimization. To be valid, the comparison should not be based on random designs, but rather on designs optimized with the same targets and constraints.

Here, a TFPM topology is chosen for the analysis. The chosen TFPM machine and the Conventional PM Synchronous machine are optimized with the same constraints, that are nominal powers, efficiencies, outside diameters and rotational speeds. The optimization target is cost/torque.

Optimization of these two machine topologies is achieved

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via a set of analytical equations, leading to an acceptable computing time. For the TFPM machine, the three-dimensional analytical model is based on linear equivalent circuits of lumped reluctances.

II. DESCRIPTION OF TFPM MACHINE TOPOLOGIES AND SELECTION OF A TFPM TOPOLOGY

At least eleven different TFPM geometries have been described in the past scientific literature. They can be split into two main families: surface-mounted TFPM machines and flux-concentrating TFPM machines. A few publications [5]-[8] have highlighted that flux-concentrating TFPM machines provide higher force density compared to surface-mounted machines. This is a consequence of a higher leakage flux between rotor poles at no-load. As we are concerned with cost reduction of active material, the remainder of this paper only focuses on the flux-concentrating TFPM machine topologies.

At least seven flux-concentrating TFPM geometries have been proposed in literature. They are described in detail in [8]. We give a brief description of those machines in this section.

A. Double-sided, double-winding and single-winding TFPM machines in U-core arrangement

The double-sided TFPM machine with double-winding [5] is shown in fig. 1. It comprises a set of U-cores made of laminated steel enclosing two stator windings, one on each side of the rotor.

The rotor is located in between the two windings and is made of permanent magnets and flux concentrators. The PMs are magnetized parallel to the direction of motion with alternate polarities. Each Ucore encloses a winding and closes the magnetic circuit for the U-core on the other side.

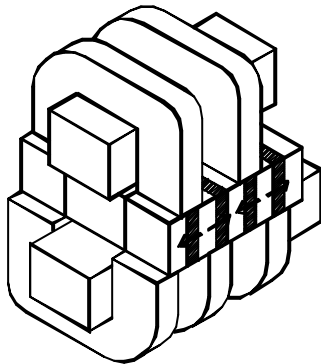


Fig. 1. Double-sided, double-winding TFPM machine

The double-sided TFPM machine [9] with single-winding in U-core arrangement is shown in fig. 2.

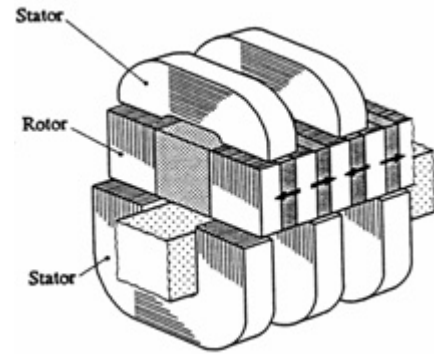


Fig. 2. Double-sided, Single-winding; U-Core arrangement

Removal of one of the two windings does not affect the machine torque rating. Although, the no-load voltage is twice lower than if two windings were used, the reluctance of the magnetic circuit is the same for one or two windings. Thus, when current flows in a single winding, saturation of the stator cores is reached at twice the current value of a double-winding arrangement. Hence, the amount of material used for a given torque rating should in principle be the same for the single-winding and the double-winding versions.

Nevertheless, the single-winding configuration has the two following advantages:

- elimination of the top winding, which is difficult to mount and maintain inside the outer U-cores;
- reduction of the machine outer diameter, making a better use of the inner part of the machine.

Moreover, we readily see how the rotor is “sandwiched” between the two stators, both in fig. 1 and fig. 2. This will possibly lead to thicker air gaps, due to deformations of the difficult rotor arrangement. A thicker air gap reduces the no-load flux entering the stator cores, and consequently reduces the no-load voltage and torque rating.

B. Double-sided, single-winding; C-core arrangement

The double-sided, single-winding TFPM machine with C core arrangement [9] is illustrated in fig. 3. This design is obtained from the Ucore concept of fig. 2 by replacing one row of permanent magnets by ferromagnetic material.

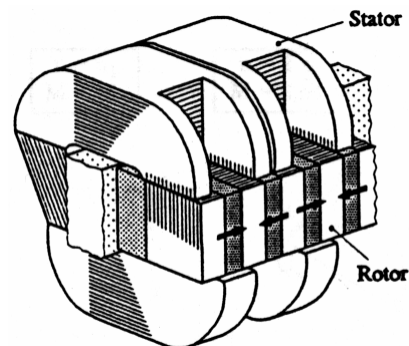


Fig. 3. Double-sided, single-winding; C-core arrangement

The use of powdered iron appears as a natural material for this type of construction. A variant of this machine [10] uses

powdered iron and is shown in fig 4.

Magnetically speaking, this type of design uses flux concentration in the same way as with the double rows of magnets of fig. 2. Fig. 2 and fig. 3 will have comparable no-load flux linkage, because half the magnets are removed, but half the air gaps are also removed.

In addition, removal of two airgaps in the main magnetic path decreases the reluctance “seen” by the stator winding. Thus, the saturating magnetomotive force to be fed into the stator coil is also reduced by a factor 2. Consequently, if the same dimensions are used in both cases, we can expect the torque density (torque per volume) to be roughly half of the torque density of the U-core version.

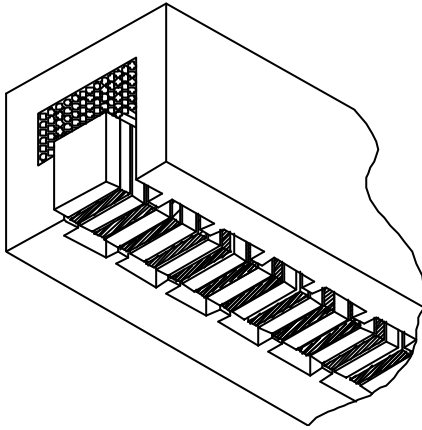


Fig. 4. Double-sided, Single-winding TFPM machine with C-Core arrangement. Design proposed in [10].

Looking at the prototype built in [10] with this machine configuration, a torque density of 50.8 kNm/m^3 was obtained for a diameter of 360 mm. In comparison, the prototype built in [11] of the TFPM machine shown in fig. 2 gave a torque per volume of 96.3 kNm/m^3 , which is about twice as high.

Regarding the amount of material required in the C-core arrangement, the amount of PM material is divided by 2 compared to fig. 2. The mass of copper is also divided by 2, since half the current is fed into the machine due to the lower stator reluctance. Roughly, we can expect that the cost of active material will be about half, for half the torque of the TFPM machine of fig. 2. Thus, the cost/torque of this concept should be comparable to the values obtained with the U-core arrangement of fig. 2.

It appears that the construction can be simplified with the use of a powdered iron stator. However, molding a complete stator in one powdered iron piece is also a problem, due to the rating of the hydraulic press. Often, a large number of blocks of powdered iron will be necessary to form the complete stator. This adds to the construction complexity.

The problem of the double-sided air gap is also applicable to this machine topology. They are related to the tight mechanical tolerances and equal thermal expansion coefficients required

on the stator and rotor parts for this type of “sandwiched” construction.

C. Clawpole TFM

The Clawpole TFM machine [13][14] is illustrated in fig. 5. Obtaining the clawpole TFM structure of fig. 5 from fig. 4 is accomplished via the following steps:

- the rotor is taken out from in between the stator feet;
- the rotor width l_{rl} is increased to match the stator width;
- the stator foot length l_f is made longer in the axial direction, in order to catch more flux from the rotor;
- the cross section (product $l_{leg}w_{sc}$) of the stator foot is made generally constant, as we move away from the airgap.

The stator core can be wide (large width w_{sc}) near the winding and narrow (short width w_{sc}) near the airgap.

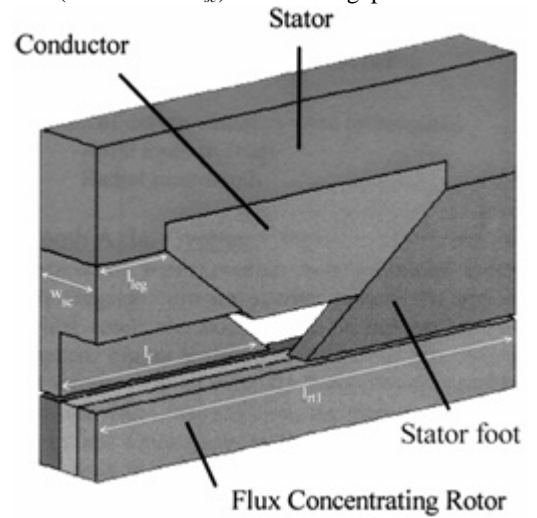


Fig. 5. Clawpole TFM.

A stator core with a large cross-section (product $l_{leg}w_{sc}$) is desirable because it allows a high magnetomotive force in the stator coil before saturating the core. Moreover, if the stator core is made thin near the air gap, the leakage in the air gap area can be kept low.

The clawpole TFM also has the advantage of a single-sided rotors, which makes its mechanical construction much stiffer than the previous double-sided TFPM machines.

If we compare the clawpole TFM machine built in [14] to the double-sided machine with C-core arrangement built in [10], the two machines have diameters of 340 mm and 360 mm and an axial length of 60 mm. They both use almost the same amount of active material, i.e. 22.7 kg and 20.8 kg. They both have the same airgap thickness, i.e. 0.5 mm. The clawpole TFM machine has a rated torque of 540 Nm and the double-sided, single-winding TFPM machine with C-core arrangement has a rated torque of 310 Nm.

D. E-core TFPM

The Ecore TFPM machine [9] is shown in fig. 6. It reduces the rotor width in the axial direction, allowing a reduction of the

rotor deformations due to centrifugal forces.

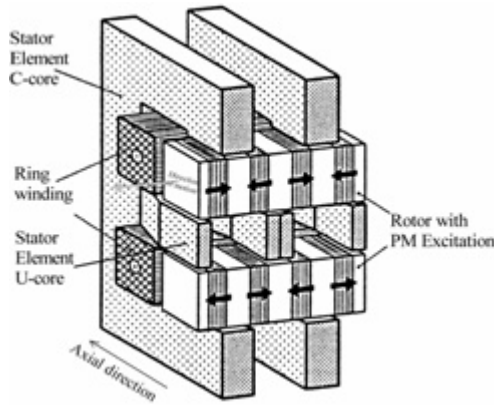


Fig. 6. TFPM machine with E-core configuration.

The stator is made of two separate parts, that is a C-core surrounding both stator windings and a U-core placed in between the two windings. Electromagnetically, this concept has the same expected performances as the double-sided, double-winding TFPM machine discussed previously.

In production, this type of design will also encounter the same problems as with the double-sided, double-winding TFPM machine discussed previously, with the addition of the difficulty of laminating the U-core in between the two windings. In that case, powdered iron may be used or metallic glass tape (METGLAS). In the latter case, the cost of metallic glass material is high, which is probably not a suitable solution for cost reduction. Another major difficulty in this type of design is the presence of four air gaps, which requires a very stiff and very accurate mechanical concept.

E. TFPM machine with toothed rotor

The TFPM machine with toothed rotor [15] is shown in fig. 7 and fig. 8. It has the following characteristics: a) permanent magnets in flux concentration, b) stator cores built with laminated steel, c) single-sided stator, d) location of each magnet in the rotor is independent from the sum of mechanical tolerances due to the other rotor pieces, e) magnet and flux concentrators can be built and inserted in the rotor structure using an automated process.

1) Production of flux-concentrating TFPM machines

Many 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.

The stator winding of most TFPM machines is very simple. However, other parts of past TFPM machines present important production difficulties. In flux-concentrating configurations, the rotor construction can be substantially improved by using a toothed rotor structure. Such structure can be made from a stack of laminations, where each lamination is stamped individually from a die of alternating teeth and slots. This kind of arrangement is also comparable to the stator

of conventional synchronous machines. The toothed laminations are shown in fig. 9.

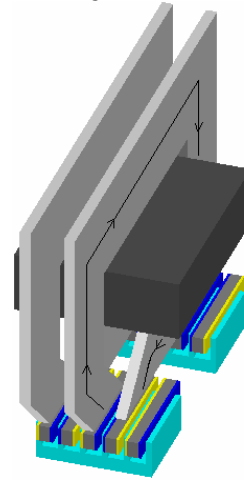


Fig.7. Five poles of the TFPM machine with toothed rotor (linear version).

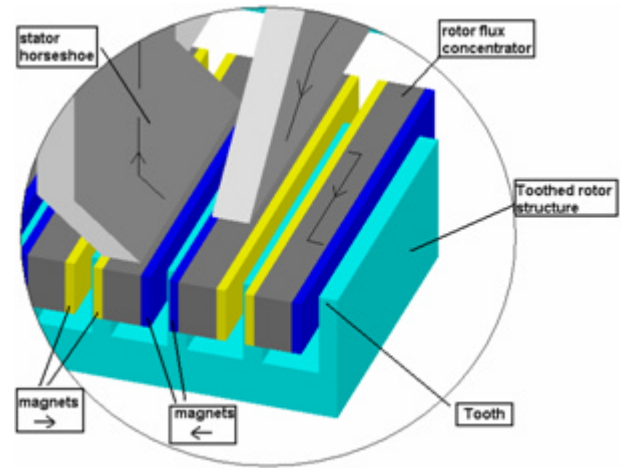


Fig.8. Close-up on the TFPM machine with toothed rotor.

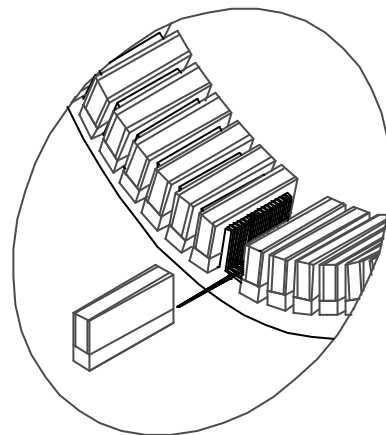


Fig.9. One row of the laminated rotor structure (stator is not shown).

Each rotor pole can be assembled independently, outside the machine. Then each sub-assembly can be inserted into the toothed rotor structure, as shown in fig. 9. For each pole, rotor sub-assemblies are formed by two magnets with opposite directions of magnetization, one flux concentrator and one insulating block.

The insulating block prevents short-circuiting the magnet fluxes through the toothed structure. Also, the insulating block and the slot may be designed with a trapezoidal shape, offering natural retainment of the rotor poles inside the slots.

2) Use of laminations in the stator

The TFPM machine with toothed rotor allows laminated steel to be used in the stator parts, due to the planar flux circulation. Laminated steel gives better performance than powdered iron, as long as the magnetic flux travels parallel to the lamination planes. A very important difference between powdered iron and laminated steel is the specific iron losses. They are about 7 times lower in 0.35-mm thick laminated electric steel at 400 Hz [15] in the case of planar flux circulation. This point is of utmost importance in TFPM machines, where pole pitches are short and consequently electrical frequencies are rather high.

3) Reducing leakage between the stator cores

One significant problem in single-sided TFPM stators is the stator leakage flux between the stator horseshoe and the core forming the return path. In the proposed structure, the problem is dealt with, by forming the return path into a trapezium and by shaping the horseshoe core with a leg and a foot. This reduces the area of flux leakage between the two stator cores.

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 length of the stator foot is made a little shorter than the flux concentrator, thus reducing 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.

III. OPTIMIZATION OF THE TFPM MACHINE WITH TOOTHED ROTOR AND THE CONVENTIONAL PM SYNCHRONOUS MACHINE

In the last section, several TFPM topologies have been discussed and a new geometry has been proposed, which fulfills the criteria of improved manufacturing and use of laminations in the stator. In the rest of the paper, the choice is made to analyze the TFPM machine with toothed rotor in detail and investigate how it compares with the conventional PM synchronous machine, which is illustrated in fig. 10.

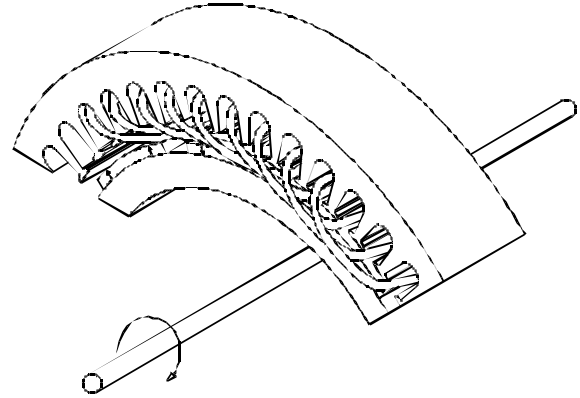


Fig.10. Conventional PM synchronous machine.

Optimization programs are written for both machine types. The machine designs with the best cost/torque are extracted. For both machine topologies, the following parameters are given as constant inputs of the optimization process:

- machine outer radius r_{out} ;
- efficiency η at full load;
- rotational speed, as indicated in Table 1.

TABLE I
MACHINE ROTATIONAL SPEED AS A FUNCTION OF THE GENERATOR OUTSIDE DIAMETER.

Generator outside diameter (m)	0.5	1.0	2.0	3.0
Wind turbine power range (kW)	10 - 30	30 - 100	100 - 200	400 - 600
Nominal rotational speed (rpm)	130	75	46	34

Costs are calculated by assuming the following specific costs:

- copper: 6 Euros/kg;
- steel lamination and powdered iron: 6 Euros/kg;
- permanent magnets: 40 Euros/kg.

Manufacturing and magnetically-inactive material are not considered in the cost calculations.

The optimization programs calculate the cost/torque of thousands of designs of TFPM machines with toothed rotor for efficiencies of 90% and 95%. The programs identify the design having the lowest cost/torque. Then the best design is fed into a 3-D finite element software for validation. Torque and efficiency are adjusted accordingly.

Then, the programs calculate thousands of designs of conventional PM synchronous machines having the same torque value as the optimized design of the TFPM machine with toothed rotor, and identify the conventional PM synchronous machine with the lowest cost of active material.

The following assumptions are used in the calculation of both machine topologies:

- the number of phases is 3;
- the machine has sinusoidal terminal voltage $v(t)$, no-load voltage $e(t)$ and phase current $i(t)$;

- the machine rotational speed ω_m is constant;
- sufficient forced air or liquid cooling is provided to maintain the PMs and copper within their operating temperature range. In the calculation of copper losses, the resistivity value for copper assumes a copper temperature of 100 degrees Celcius;
- all PMs are Nd-Fe-B with rigid remanent flux density of 1.1 T and linear recoil permeability $\mu_{rec} = \mu_0$;
- all steels have linear $B(H)$ characteristics with slope $\mu_{rFe} = 1000$ up to the point of saturation of 1.8 T;
- the air gap thickness g is equal to 1/1000th of the machine outside diameter;
- the slot filling factor is set to 0.6 for diameters larger than 2 meters and to 0.4 for diameters below 2 meters. In the first case, square conductors are used. In the second case, round conductors are used;
- the specific eddy current losses in Fe-Si laminations at 50 Hz/1.5 T are set to 0.5 W/kg;
- the specific hysteresis losses in Fe-Si laminations at 50 Hz/1.5 T are set to 2.0 W/kg;
- additional iron losses due to the punching and soldering process on the stator laminations are taken into account by multiplying all iron losses by a factor 2. This factor also takes into account the additional losses caused by the frequency harmonics in the phase current and no-load flux density.

A. Optimization of the Conventional PM Synchronous Machine

The calculation of cost and torque rating of the conventional PM synchronous machine is based on conventional analytical models, which assume that the magnetic fields cross the air gap perpendicularly. The analytical model is classical and is well described in [8]. The following parameters are used as variable inputs of the optimization process:

- current density J ;
- pole pitch τ_p ;
- ratio of slot width/ tooth width (b_s/b_t);
- no-load flux density B_g in the air gap;
- ratio of stator axial length / outer radius l_s/r_{out} .

In addition to the assumptions listed above, the following assumptions are used for the conventional PM synchronous machine:

- the number of slots per pole per phase is $q = 1$ and the winding is a two-layer full-pitched winding;
- the PM cover a pole arc of 126 degrees.
- for each phase, all the stator coils are connected in series;
- rotor saliency is neglected;
- stator slots are skewed by one slot pitch;
- the slots are open and a non-magnetic wedge of thickness $h_w = 5$ mm is inserted in the opening;
- the slots are deep with a ratio $h_s/b_t = 4$. For mechanical reasons, the ratio of slot depth over tooth width is limited to

- 4, which prevents excessive tooth mechanical vibrations from occurring;
- the maximum flux density in the stator yoke and the rotor back iron are set to 1.2 T, in order to reduce the drop of magnetomotive force in those parts. This also reduces the iron losses in the stator yoke;
- rotor iron losses are neglected;
- the flux linkage under full-load condition is made equal to the no-load flux linkage;

The rms no-load voltage E is calculated by using (1).

$$E = \frac{4}{\sqrt{2}} p N_{slot} k_{ws} k_p k_d A_p \hat{B}_1 f \quad (1)$$

where p is the number of pole pairs, k_{ws} is the skewing factor, which takes into account the reduction of emf due to slot skewing. N_{slot} is the number of conductors inserted in one slot, A_p is the area covered by one pole, \hat{B}_1 is the amplitude of the air gap flux density fundamental frequency. The factors k_p and k_d are the pitch factor and the distribution factor and are equal to 1.

The machine terminal voltage at full-load is made equal to the no-load voltage, to obtain equal flux linkages and avoid saturation under full-load condition. The phasor diagram of fig. 11 is considered.

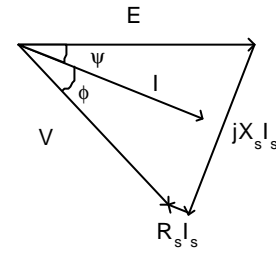


Fig.11. Phasor diagram used for the conventional PM synch. machine.

B. Optimization of the TFPM machine with toothed rotor

To optimize the design performance of the TFPM machine with toothed rotor, an analytical model based on equivalent reluctances is used. This model is described later on.

The analytical model poses a relationship between the machine geometrical parameter and lumped reluctances. Each lumped reluctance is modeled independently by feeding the results of finite element calculations into a curve-fitting process [8]. The optimization is done by varying the following geometrical parameters of the TFPM machine with toothed rotor:

- magnet thickness h_m ;
- stator core width w_{sc} ;
- flux concentrator width w_{rc2} ;
- rotor tooth width w_{rc1} ;
- flux concentrator length l_{rl} ;
- ratio of stator foot length over flux concentrator length l_f/l_{rl} ;
- magnet radial dimension ω_m ;
- conductor current density J ;

--phase angle ψ .

Once the optimal cost and torque values are calculated using the linear analytical model, the resulting design is passed through a single 3-D finite element simulation, as mentioned above. This step allows better accuracy[8]. The torque value obtained from this finite element calculation is the one used in the final cost/torque evaluation.

C. Analytical model used for the TFPM machine with toothed rotor

The average torque T of a single-phase machine with salient poles can be expressed as:

$$\bar{T} = \frac{EI \cos y + p I^2 f(L_u - L_u) \sin 2y + P_{Fe}}{w_m} \quad (2)$$

when the no-load voltage and phase current are assumed as sinusoidal. In (2), P_{Fe} is the iron losses and ψ is the phase angle. The stator inductance is assumed as varying sinusoidally with the electrical angle, between two values L_u and L_d .

Eq. (2) is written as a function of the global electrical quantities E, I, L, f, ω_m . In [8], a similar expression for T is derived, expressed on a per pole-pair basis:

$$\bar{T} = \frac{p^2}{2} \left[F_{smax} \Phi_{pnl} \cos y + \frac{F_{smax}^2}{4} \left(\frac{1}{R_{ap}} - \frac{1}{R_{up}} \right) \sin 2y \right] + \frac{P_{Fe}}{w_m} \quad (3)$$

where F_{smax} (in A-turns) is the peak magnetomotive force created by the stator winding, Φ_{pnl} is the no-load flux per pole pair (in Wb) and R_{ap}, R_{up} are the reluctances of a single pole pair seen by the stator winding.

1) Calculation of F_{pnl} and R_{ap}

In TFPM machines, the pole pitch is generally short. This makes the flux calculation difficult, due to the different leakage paths directed in all 3 dimensions. The leakage flux paths and main paths are shown in fig. 12 and fig. 13. From these two figures, an equivalent magnetic circuit may be derived, which is shown in fig. 14. The values of Φ_{pnl} and R_{ap} are obtained by solving the magnetic circuit of fig. 14 and the resulting expressions are detailed in [8].

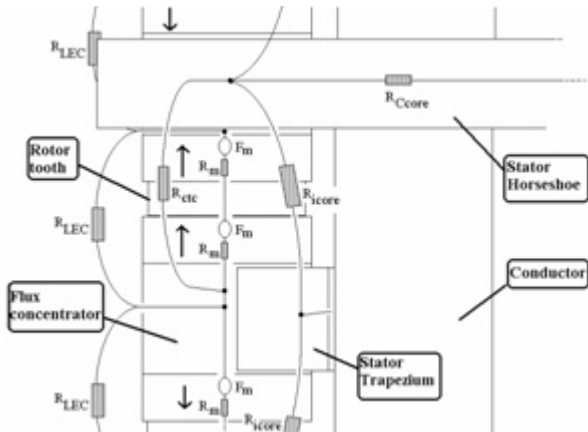


Fig. 12. Leakage paths of the TFPM machine with toothed rotor, represented as lumped reluctances in the aligned position (top view).

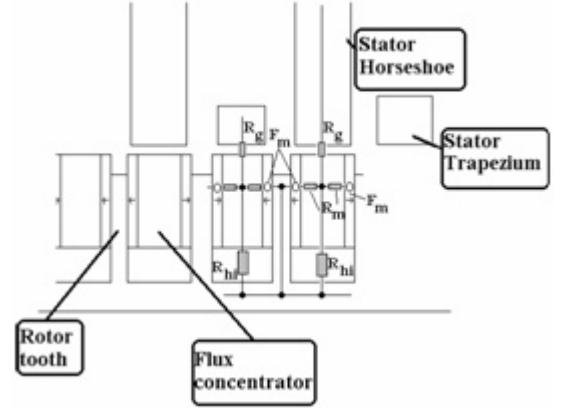


Fig. 13. Leakage paths of the TFPM machine with toothed rotor, represented as lumped reluctances in the aligned position (side view).

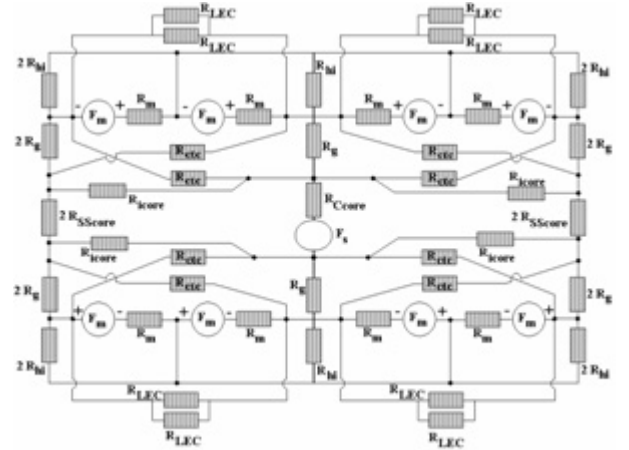


Fig. 14. Magnetic circuit of the TFPM machine with toothed rotor in the aligned position.

2) Calculation of R_{up}

The magnetic circuit in the unaligned position is defined from the lumped reluctances shown in fig. 15. The equivalent magnetic circuit in the unaligned position is shown in fig. 16. Solving the equivalent circuit of fig. 16, the reluctance R_{up} can be obtained. The derivation of the analytical expression is given in [8].

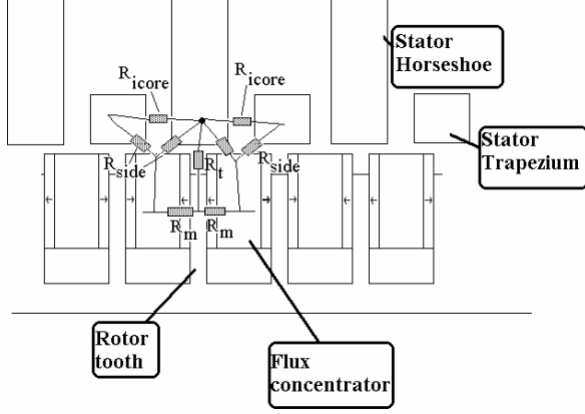


Fig. 15 Leakage paths of TFPM machine with toothed rotor, represented as lumped reluctances. Unaligned position (side view).

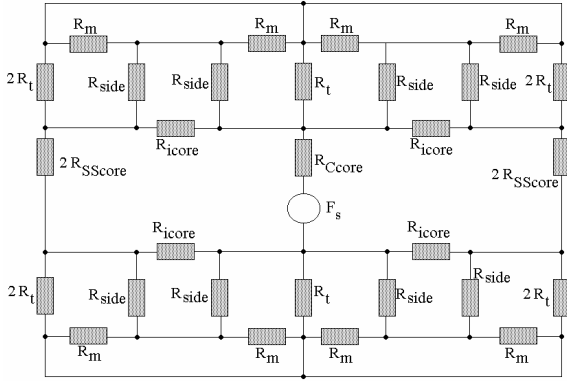


Fig. 16. Magnetic circuit of the TFPM machine with toothed rotor used for the calculation of R_{up} .

3) Calculation of F_{smax}

The total flux flowing in one stator core of the TFPM machine is composed of the no-load flux per pole $\Phi_{pnl}(t)$ and the flux $\Phi_{ps}(t)$ created by the armature reaction. F_{smax} is chosen as to maximize (3), without saturating the stator core. The latter condition is achieved by satisfying (4).

$$\left| \Phi_{pnl} \sin(\omega t) - \Phi_{ps}(t) \right| \leq \Phi_{psat} \quad (4)$$

where Φ_{psat} is the saturation flux of one single stator core. The calculation of $\Phi_{ps}(t)$ and F_{smax} is detailed in [8].

IV. COMPARISON BETWEEN TFPM WITH TOOTHED ROTOR AND CONVENTIONAL PM SYNCHRONOUS MACHINE

The cost/torque of the TFPM with toothed rotor is compared with the conventional PM synchronous machine for diameters ranging between 0.5 m and 3.0 m. The results are presented in fig. 17.

The cost/torque of the TFPM machine with toothed rotor is lower for diameters of 0.5 m and 1.0 m. However, for diameters of 2.0 m and above, the conventional PM synchronous machine has lower cost/torque. This is explained by the thicker air gap at larger diameters. Thick air gaps create

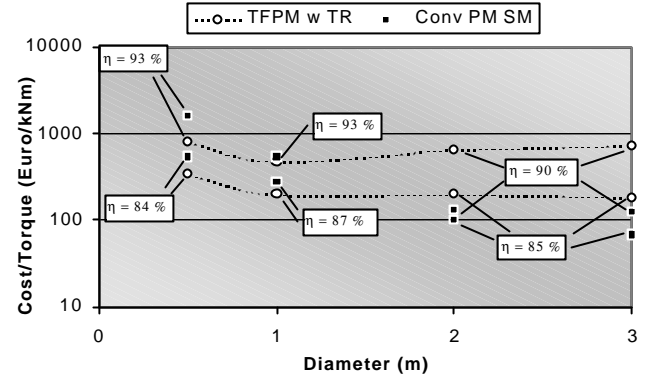


Fig. 17. Cost/torque performance after optimization of the TFPM machine with toothed rotor and conventional PM synchronous. Results on the TFPM machine are taken from FEA calculations. Optimization target: lowest cost/torque. Dotted lines = cost/torque of TFPM machine with toothed rotor.

significant flux leakage in the TFPM machine with toothed rotor. To compensate the increase in flux leakage, a larger pole pitch is required. It appears that the TFPM machine with toothed rotor is a valuable option as long as its optimized pole pitch can be kept significantly lower than the pole pitch of the conventional PM synchronous machines.

From fig. 17, a conventional PM synchronous direct-drive generator of 3-meter diameter with an efficiency of 90%, would have a cost/torque of 120 Euros/kNm. For a 600-kW wind turbine rotating at 34 rpm with a torque of 187 kNm, we can expect the cost of the generator active material to be about 23,000 Euros. With an approximate cost of 1 Euro/Watt for a complete wind turbine, a 600-kW wind turbine would cost around 600,000 Euros. Therefore, the cost of the generator active material would represent about 4% of the total turbine cost. It is widely accepted that the cost of a wind turbine direct-drive generator is well above 4% of the total turbine cost. Therefore, it appears that active material alone does not suitably define the production cost of a direct-drive generator. We recommend to include the cost of the inactive material and manufacturing to obtain more accurate cost figures.

V. CONCLUSION

The cost/torque comparison between TFPM machines with toothed rotor and conventional PM synchronous machines was investigated. For diameters of 1.0 m and below, lower cost/torque is obtained with the TFPM machine with toothed rotor. However, diameters larger than 1.0 m favor the conventional PM synchronous machine, because of the larger air gap used. Efficiency also plays a dominant role in the cost/torque of both machine topologies.

We also recommend that more attention be paid to the optimization of the mechanical design and manufacturing costs.

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