Effect of Air Gap Thickness on Transverse-Flux Permanent Magnet (TFPM) Machines with Flux-Concentration

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Abstract — The use of Transverse-Flux Permanent Magnet (TFPM) machines for high-torque and low-speed application is investigated. The ability of TFPM structures with flux-concentration to reduce the cost of active material is looked upon more closely. The Cost/Torque characteristics of TFPM (Transverse-Flux Permanent Magnet) machines and Conventional Permanent Magnet Synchronous machines are presented. It is emphasized how the air gap thickness plays a dominant role in the cost savings provided by the TFPM structure. For air gap of 0.5 mm, the TFPM structure with flux concentration discussed in the paper shows important cost benefits, over the Conventional Permanent Magnet Synchronous machine. Above the 3.5 mm threshold, the TFPM with flux concentration does not show such great cost advantages over the Conventional Permanent Magnet Synchronous machine.

1. Introduction

Many applications require electrical machines with high torque and low speed. Such applications are: wind turbine generators, ship propulsion motors, bus traction motors. The use of a gearbox with a low-torque machine is often preferred to the direct-drive machine with high torque, mainly because of the high costs of direct-drive electrical machines.

To reduce the cost of the direct-drive machines, the use of Transverse-Flux Permanent Magnet (TFPM) structures is investigated. TFPM machines make possible the use of short pole pitches in combination with high current loading. In most TFPM machine prototypes built, this gives a torque over mass ratio higher than conventional machines. A reduction in the active mass will also lead to a reduction in the cost of active material. The costs for active material for the TFPM machine with flux-concentration and for the Conventional Permanent Magnet Synchronous machines (PMSM) are compared. Both machine types are modeled and optimization programs are developed, which target the lowest cost/torque for generator diameters between 0.5 m to 4 m. Attention is paid to the effect of airgap thickness on the cost/torque ratios of both machine types.

2. Machine structures investigated

Among the several topologies of the TFPM concept, the TFPM machine with double-sided air gap and flux-concentration is chosen for this investigation. This structure was proposed in [1], and is shown in fig. 1. As discussed in [2], TFPM structures with flux-concentration make a better use of the PM material, and have higher air gap flux density than TFPM machines with surface magnets.

Fig. 1. TFPM machine with flux-concentration. Linear representation.

This TFPM structure is chosen, because it was the first TFPM structure with flux-concentration proposed in the literature, and from which most other TFPM structures with flux-concentration (as in [3]) are derived. The conclusions of this paper will apply to most of TFPM machines with flux-concentration.

The second machine structure analyzed in the paper is the Conventional PMSM, shown in fig. 2.

Fig. 2. Conventional PM Synchronous machine.
A. Cost over Torque ratio

The criterion “cost over torque” is used in order to compare the two PM machine geometries. For each of the two machine types, the cost of active material is computed by weighting each material with a given specific cost:
- specific cost of laminated steel = 6 Euro/kg
- specific cost of copper = 6 Euro/kg
- specific cost of PM = 40 Euro/kg
- specific cost of powdered iron = 6 Euro/kg

3. Performance of TFPM and Conventional PMSM with increasing air gaps

Appendix I describes the analytical models used for torque computation. Using the machine models developed in Appendix I, two optimization programs were developed, which vary all geometrical parameters, and calculate the corresponding torque and corresponding cost. The programs retain the lowest value of the cost over torque ratio. For the TFPM machine, the torque of the optimal design is checked by implementing the cost-optimal geometry in a 3-D finite element analysis (FEA) software.

Optimal designs of the Conventional PMSM and TFPM machine are calculated for diameters varying between 0.5 m and 4 m, and for air gap thickness varying between 0.5 mm and 4 mm. The resulting cost over torque ratios are presented in fig. 3 and fig. 4.

Inspection of fig. 3 indicates only little influence of the air gap thickness on the cost over torque ratio, in the case of the Conventional PMSM. For the TFPM machine, the cost over torque ratio (fig. 4) is much more sensitive to air gap thickness variations. It must be noted that the optimization process targeted machine designs with similar efficiencies (fixed to 92% in this case). The efficiency has a significant influence on the cost over torque ratio, which is not covered in the paper.

Fig. 5 shows the TFPM cost advantage factor $K_{TFPM\_Cost}$ as defined by (1).

$$K_{TFPM\_Cost} = \frac{\text{Cost/Torque\_PMSM}}{\text{Cost/Torque\_TFPM}}$$

Fig. 5 shows that the TFPM machine with flux-concentration provides a significant cost advantage over the Conventional PMSM for an air gap of 0.5 mm. However, this advantage is reduced when the air gap increases. The TFPM machine with flux-concentration is a good choice for cost reduction in active material. However, the air gap thickness should be maintained below 3 mm, in order to provide a good cost advantage. Fig. 3 and 4 also indicated that increasing the diameter also reduces the cost of active material. An interesting combination for cost reduction would be to use a TFPM machine with flux-concentration, with a large diameter and a thin air gap.

4. Causes of TFPM sensitivity to air gap thickness

The strength of the TFPM machine is the high degree of
freedom on the pole pitch value. To make the no-load voltage as high as possible, a short pole pitch is normally selected. The drawback of short pole pitches is the presence of strong leakage paths between adjacent flux concentrators. The increase in air gap thickness will increase the air gap reluctance \( R_g \), without changing the reluctances \( R_{LEC} \) and \( R_{ctc} \) of the leakage paths. These leakage paths are modeled as lumped reluctances in fig. 6.

While a 1-mm air gap favors TFPM designs with pole pitches around 10 mm, a 4-mm air gap will favor TFPM designs with pole pitches around 25 mm. According to (9), a same torque is obtained, if the decrease in the number of poles is compensated by an increase in the maximum stator mmf, and an increase in the no-load flux density \( \Phi_{pnl} \). The increase in maximum stator mmf also increases the winding window area, the mass of copper winding and the size of the stator cores. Thus, the thicker the air gap thickness, the higher the mass of PM material, copper and iron required for a given torque.

5. Conclusion

The cost over torque ratios of TFPM machines with flux concentration and Conventional PMSM have been investigated. Analytical models have been developed for both machine types. Optimization programs have been developed, allowing the prediction of designs with the lowest cost over torque ratio.

The results of the optimization process are obtained for machine diameters between 0.5 m and 4 m and for air gap thickness of 0.5 mm and 4 mm. The cost over torque ratio of the Conventional PMSM shows a low dependency from the air gap thickness, while the TFPM machine with flux concentration is much more dependent. The TFPM machine with flux concentration shows a cost advantage factor of about 3.5 with an air gap thickness of 0.5 mm. The cost advantage factor decreases to about 1 as the air gap thickness increases to 4 mm. Direct-drive applications can benefit from a TFPM machine with a large diameters and a thin air gap. But in that case, further attention should be given to the mechanical design of such machines.

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References

Appendix I: Mathematical models

The Conventional PMSM and TFPM machine are compared on the basis of their cost over torque ratio. The two machine types have a large number of geometrical parameters, which can be varied independently, giving out millions of different design possibilities for a same torque rating. To identify the design with the lowest cost over torque ratio, a computer program has been developed for the two machine types. The programs predict the machine torque and cost for each set of geometrical parameters, and allow these geometrical parameters to vary within a certain range.

A. Conventional PMSM: analytical model

The optimization program predicts the torque performance for the Conventional PMSM from its geometrical parameters. The machine torque $T$ is derived from (2).

$$T = \frac{P_{\text{mech}}}{\Omega} = mEI \cos \delta \Omega$$

where the no-load losses are neglected, and where the no-load voltage and phase current are assumed as sinusoidal. $E$ is derived by using (3), (4) and (5) where (4) was obtained from a 2-D finite element calculation in [4].

$$E = \frac{4}{\sqrt{2}} \pi k_{ws} B_1 r_j l_j f N_{\text{slot}}$$

$$B_1 = \sqrt{2} B_t \left[ 0.81 - 0.3 \left( \frac{h_s + g}{r_p} \right) \right]$$

$$B_g = \frac{\Phi_g}{l_s k_{mag}}$$

Equation (4) is valid for $k_{mag} = 0.7$. This value has been used in all calculations.

In (3), the stator is assumed as skewed, and $k_{ws}$ is set to 0.95 in the program. The value of $\Phi_g$ is obtained by assuming the magnetic field as traveling in straight lines through the magnetic circuit of fig. 8.

In the calculation of $R_{\text{stat,teeth}}, R_{\text{stat,yoke}}, R_{\text{rot,back}}$, a constant permeability $\mu_{Fe}$ was used and consequently the machine has been assumed to work below saturation.

The nominal phase current $I$ is calculated with (6) and (7).

$$I = JA_{\text{Cut}}$$

$$A_{\text{Cut}} = k_{glt} \left[ b_l (h_s - h_u) / N_{\text{slot}} \right]$$

In the calculations, the following values are used:

- $J = 4.0 \text{ A/mm}^2$
- $k_{glt} = 0.5$
- $m = 3$
- $h_u = 5 \text{ mm}$
- slot depth/slot width $(h_s/b_s) = 4$
- slot width/tooth width = 1.05
- $B_t = 1.23 \text{ T}$
- $\mu_{Fe} = 1000$
- $\mu_m = 1.09$
- $B_{Fe sat} = 1.9 \text{ T}$
- $\delta = 0 \text{ degree}$
- $q = 1$
- $N_{\text{slot}} = 2$

B. TFPM machine: analytical model

The TFPM machine is essentially a single-phase machine. It is possible to turn it into a three-phase machine, by stacking three TFPM machines, and shifting their rotors by $120^\circ$. The torque of a single-phase machine with salient poles can be expressed as:

$$T = \frac{EI \cos \delta}{\Omega} + \frac{\pi / 4 (L_u - L_s)}{2\Omega} \sin 2\delta$$

where the no-load losses are neglected and where the no-load voltage and phase current are assumed as sinusoidal. The stator inductance is assumed as varying sinusoidally with the electrical angle, between two values $L_u$ and $L_s$.

Expression (8) is written as a function of the global electrical quantities $E$, $I$, $L$, $f$, $\Omega$. We can also derive a similar expression for $T$, expressed on a per pole-pair basis:

$$T = \frac{P_{\text{mech}}}{2} \left[ \frac{\Phi_{glt} \cos \delta}{4} + \frac{F_r}{R_{np}} \left( \frac{1}{R_{np}} - 1 \right) \sin 2\delta \right]$$
**Calculation of \( \Phi_{pnl} \) 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. 6. The magnetic circuit of fig. 9 represents the combinations of leakage and main paths in the aligned position, modeled by lumped reluctances.

![Magnetic circuit used to determine \( \Phi_{pnl} \) and \( R_{ap} \)](image)

The values of \( \Phi_{pnl} \) and \( R_{ap} \) are obtained by solving the magnetic circuit of fig. 9, which gives:

\[
\Phi_{pnl} = \frac{F_c(R_m - 2R_s)}{R_sR_l + 2R_m \left( \frac{2R_sR_c + R_l + R_s}{R_m} \right) + \left( R_{ctc} + R_{LEC}, \frac{R_{ctc} + R_{LEC} + R_s + R_c}{R_m} \right)}
\]

and

\[
\Phi_{pnl} = \frac{R_{Ccore} + R_{SScore} + R_{12} + (R_{12} + R_{ap})(R_{12} + 2R_s)}{R_{12} + R_{ap} + 2R_s}
\]

where

\[
R_{12} = \frac{R_{LLEC}}{(R_m + 2R_s)(R_m + R_{LLEC}) + R_mR_{LLEC}}
\]

\[
R_{12} = \frac{2R_sR_{LLEC}}{(R_m + 2R_s)(R_m + R_{LLEC}) + R_mR_{LLEC}}
\]

\[
R_{12} = \frac{2R_mR_s}{R_m + 2R_s + \frac{R_mR_{LLEC}}{2R_m + R_{LLEC}}}
\]

**Calculation of \( R_{ap} \)**

The magnetic circuit in the unaligned position is somewhat simpler. Fig. 10 shows the leakage path for the flux created by the stator winding in the unaligned position.

![Side view of the TFPM machine with flux concentration and double-sided air gap, shown in the unaligned position. Only one side of the rotor is shown.](image)

The reluctance \( R_{ap} \) is then equal to:

\[
R_{ap} = 2R_{side}
\]

**Calculation of lumped reluctances**

To calculate the value of the lumped reluctances \( R_{ap}, R_{Ccore}, R_{SScore}, R_{LLEC}, R_{ctc}, R_{g} \), and the mmf \( F_m \) we use (16)-(23). Equations (20)-(23) are derived from the collection of a high number of 3-D finite element computations.

\[
R_m = \frac{h_m}{\mu_0 R_m W_m f}
\]

\[
F_m = \frac{h_m B_f}{\mu_0 R_m}
\]

\[
R_{Ccore} = \frac{l_m + 2h_m + (2\sqrt{2} + 1)l_f}{\mu_0 \mu_{Rm} W_{sf} f}
\]

\[
R_{SScore} = \frac{l_m + 2h_m - 2l_f}{\mu_0 \mu_{Rm} W_{sf} f}
\]

\[
R_{LLEC} = \frac{h_m(0.66 - 0.073b_a + 2.6 \times 10^{-4}h_c^2 + 0.012w_{c2} + 0.037w_{m2})}{b_a}
\]

\[
R_{ctc} = \frac{1}{\mu_0 f} \left[ 0.63 - 0.066 W_{v12} W_{v12} + 0.06 W_{v12} W_{v12} + 0.21 b_{a1} W_{v2} + 0.082 W_{m12} W_{m12} \right]
\]

\[
R_{ap} = \frac{g}{\mu_0 f W_{v2}} \left[ 1.6 + 0.49 \frac{d}{g} - 0.93 \frac{d}{g} - 1.04 W_{v2} W_{v2} + 0.16 W_{m2} \right]
\]
Calculation of $F_{\text{smax}}$

The torque of the TFPM machine can be predicted from (9), if the magnetomotive force $F_s$ fed into the stator winding is known. Since we are interested in the maximum $T_{\text{max}}$, the magnetomotive force $F_{\text{smax}}$ is determined from the expression of the flux $\Phi_{\text{ps}}(t)$ created by the armature reaction in the core of a salient TFPM machine, fed with a sinusoidal current.

$$\Phi_{\text{ps}}(t) = \frac{F_s}{4} \left[ \sin \delta \left[ \frac{1}{R_p} + \frac{3}{R_p'} \cos \omega t + \left( \frac{1}{R_p} - \frac{1}{R_p'} \right) \cos 3\omega t \right] \right] + ...$$

$$\frac{F_s}{4} \left[ \cos \delta \left[ \frac{1}{R_p} + \frac{3}{R_p'} \sin \omega t + \left( \frac{1}{R_p} - \frac{1}{R_p'} \right) \sin 3\omega t \right] \right]$$

(24)

The total flux flowing in one stator core of the TFPM machine is the sum of the no-load flux per pole $\Phi_{\text{pnl}}$ and the flux $\Phi_{\text{ps}}(t)$ created by the armature reaction:

$$\Phi_{\text{ps}}(t) = \Phi_{\text{ps}}(t) + \Phi_{\text{pnl}} \cos(\delta - \pi)$$

(25)

The value of $F_{\text{smax}}$ is limited by the saturation flux density $B_{\text{FeSat}}$ in the stator core. The saturation flux is defined as:

$$\Phi_{\text{psat}} = B_{\text{FeSat}} w_{l_c} l_f$$

(26)

To obtain $F_{\text{smax}}$, we vary $\omega t$ by software, between 0 and $2\pi$, and set $\Phi_{\text{psat}}$ to its saturation flux $\Phi_{\text{psat}}$ defined by (26). Using (24) and (25), we can determine a certain value of $\omega t$ for which $F_s$ is maximum.

In all calculations, the following values are used:

- $J = 5.0 \, \text{A/mm}^2$
- $k_{\text{fill}} = 0.5$
- $B_1 = 1.23 \, \text{T}$
- $\mu_{Fe} = 1000$
- $\mu_{m} = 1.09$
- $B_{l_{\text{FeSat}}} = 1.9 \, \text{T}$
- $\delta = 0 \, \text{degree}$

It must be noted that the optimization process targeted equal efficiency values for the two machine types. The targeted efficiency was 92%. This was made possible with current densities of 4 A/mm² for the Conventional PMSM, and 5 A/mm² for the TFPM machine.

Nomenclature

- $A_{\text{Cut}}$, cross-section of one conductor in the slots
- $b_s$, stator slot width
- $B_1$, Fundamental component of the no-load flux density
- $B_{\text{FeSat}}$, Saturation flux density of laminated iron
- $B_2$, no-load flux density in the air gap
- $B_r$, remanent flux density
- $d$, overlap distance between stator core and flux concentrator
- $E$, rms no-load voltage
- $f$, electrical frequency in Hz
- $F_{\text{m}}$, PM equivalent magnetomotive force (mmf)
- $F_{\text{ps}}$, peak value of the stator magnetomotive force
- $F_{\text{smax}}$, maximum value of $F_s$ obtained at saturation
- $g$, air gap thickness
- $h_m$, magnet thickness
- $h_s$, stator slot height
- $h_{\text{sw}}$, height of stator winding in TFPM
- $h_{\text{sw}}$, thickness of the stator slot wedge
- $I$, rms nominal phase current
- $J$, current density in the conductors
- $k_{\text{mag}}$, RFPM ratio of magnet width over pole pitch
- $k_{\text{fill}}$, slot filling factor
- $k_{\text{sl}}$, skewing factor
- $K_{\text{TFPM_Cost}}$, TFPM cost advantage factor
- $l_0$, length of the stator stack of laminations
- $l_2$, length of flux concentrator in axial direction
- $l_{\text{sw}}$, width of stator winding in TFPM
- $L_0$, stator inductance for rotor in aligned position
- $L_u$, stator inductance for rotor in unaligned position
- $m$, number of phases
- $N_{\text{slot}}$, number of conductors per slot
- $p$, number of pole pairs
- $P_{\text{mech}}$, mechanical power on the machine shaft
- $q$, number of slot per pole per phase
- $r_2$, air gap radius
- $R_{\text{m}}$, PM recoil reluctance
- $R_{\text{a}}$, air gap reluctance
- $R_{\text{sl,teeth}}$, reluctance of the stator teeth
- $R_{\text{sl,yoke}}$, reluctance of the stator yoke
- $R_{\text{rot,back}}$, reluctance of the rotor back iron
- $R_{\text{side}}$, TFPM reluctance of leakage path between stator core and flux concentrator in unaligned position
- $R_{\text{ap}}$, TFPM reluctance per pair seen by the stator conductors in unaligned position
- $R_{\text{ap}}$, TFPM reluctance per pair seen by the stator conductors in aligned position
- $R_{\text{Core}}$, reluctance of TFPM stator core on winding side
- $R_{\text{Sl,core}}$, reluctance of TFPM stator core on opposite side
- $R_{\text{LCC}}$, reluctance of leakage path between two adjacent flux concentrators
- $R_{\text{sl}},$ TFPM reluctance of leakage path between stator core and adjacent flux concentrator in aligned position
- $T$, average continuous torque
- $w_{\text{m}}$, magnet width in TFPM machine
- $w_{l_c}$, TFPM stator core width
- $w_{r2}$, width of flux concentrators
- $\Phi_{\text{s}}$, RFPM no-load flux in the air gap
- $\Phi_{\text{pnl}}$, TFPM no-load flux per pole in the stator core
- $\Phi_{\text{ps}}$, flux component created by the stator current in the core of a salient TFPM machine
- $\Phi_{\text{psat}}$, saturation flux in one pole of stator core of TFPM machine
- $\Phi_{\text{ps}}$, sum of no-load flux and stator-created flux in one pole of the stator core of TFPM machine
- $\mu_{\text{Fe}},$ PM recoil relative permeability
- $\mu_{Fe}$, relative permeability of laminated steel
- $\tau$, pole pitch
- $\theta$, phase angle between $E$ and $I$
- $\omega$, electrical angular frequency in rad/s
- $\Omega$, machine angular rotational speed in rad/s

\[
\begin{align*}
\text{Nomenclature} & \end{align*}
\]