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Design aspects on a transversal flux machine with SMC stator

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Abstract

Acknowledgements

Some minor work on free time between real projects.

Contents

1. Introduction

Transversal flux machines are an alternative as traction motor for electric vehicles, both landbased vehicles and airborn. The transversal flux machine can be built in several ways, see [1], but this report focuses on the variant with a soft magnetic composite material (SMC). The machine was originally investigated by Pompemaijer et.al. [2] and are now available from a company in US, ETMPOWER, [3] but as a inner rotor variant. The latter company claims patent on the stator construction as of 2010 but the main principle was known already 2007, [4]. Similar machines can be traced back in time to prof. Weh that investigated transversal flux machines in the 90's. Patent issues are not dealt with in this report.

In [1] some issues with the transversal flux machine are mentioned and that is saturation of vital parts, high leakage and low power factor.

At Chalmers we have studied several machine types including the transversal flux machine, [5,6]. The report is an attempt to overcome the short coming of the transversal flux machine as a propulsion machine. In order to find a reasonable flux weakening region it's of high interest to control the flux emanating from the winding and it shall be in the same range as the flux from the magnet. The investigated transversal flux machine have a rough stator construction which results in torque ripple and noise. So even if the mean torque could be controlled there are several challenges to overcome. One application of special interest is the electric flight application where low weight is of high importance and maybe can the noise from the machine be hidden behind the noise of propellers.

To analyse the motor, 3D-FEM has to be used in order to get a good understanding of the construction. Parallell to the FEM-calculations a reluctance model is developed. When calculating the machine size it is clear that the pole size cannot be freely chosen. The rotor acts as a flux concentrator and a prolonged axial machine results in to much magnetic flux which will saturate the magnetic parts. In the same way can an increased axial length increase the magnetic burden from the winding and a machine with unsaturated performance at noload will be heavily saturated at maximum current. Furthermore has the transversal flux machine several leakage ways that limit the performance and a good understanding on how to avoid to much flux from the winding is crucial for the performance.

The motor have a SMC stator which has some benefits. There are low amount of waste during production and the possibility to recycle the stator material are considered as easy. The draw back of iron powder material is a high hysteresis loss factor.

Three iterations of the machine are studied and the performance is altered with some changes on the pole shape. The most changes are done on the tooth and how length and cross section will influence armature reaction, saturation and core losses. It is also investigated if a reluctance model can be used for scaling the machine.

2. Fundamental flux paths

2.1 Stator

The stator can be produced from a set of pole pieces and in between these pieces a winding is easily produced with a square cross section, see Figure 1. The rotor consists of soft magnet parts and in between magnets are located. The magnets are of spoke type, i.e. the magnet direction is angular and in the same direction as the movement.

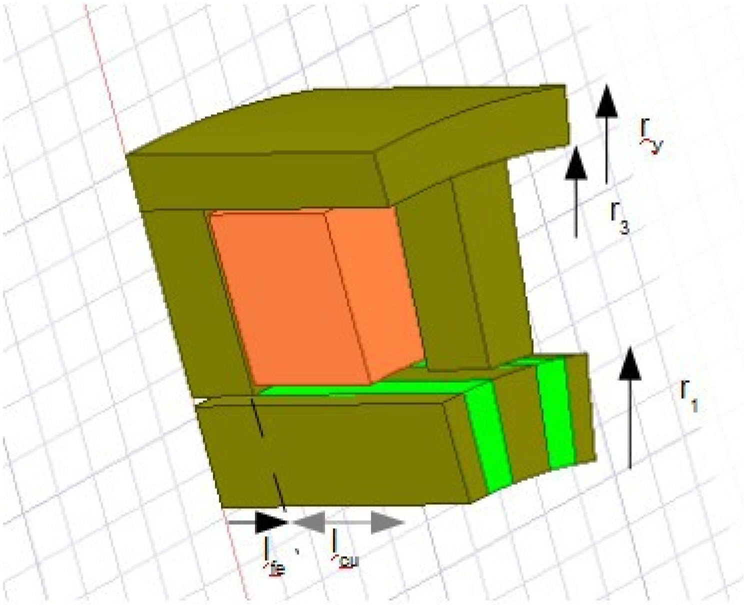


Figure 1. Stator and rotor for two poles, red is the winding and green the magnets.

The used magnetic material has the data and it resemples plastic Nd-magnets.

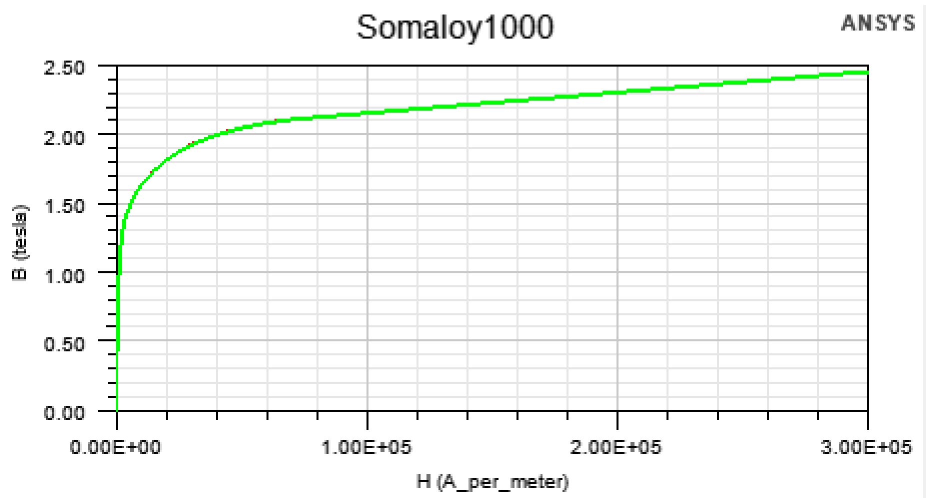
B_r=0.6 T (remanent flux density)

u_r=1 (relative permeability of the magnet)

H_c=-476000 A/m (Coercive force)

As a start the magnets are assumed lossless but there is of course a pulsating flux density in the magnets which has to be considered.

The soft magnetic material is modelled as Somaloy 1000.



- Kh	Simple	620.15896262...
- Kc	Simple	0.2976283348...
- Ke	Simple	6.3812008374...
- Kdc	Simple	0

Figure 2. Soft magnetic material

Figure 3 shows the main flux paths of the machine.

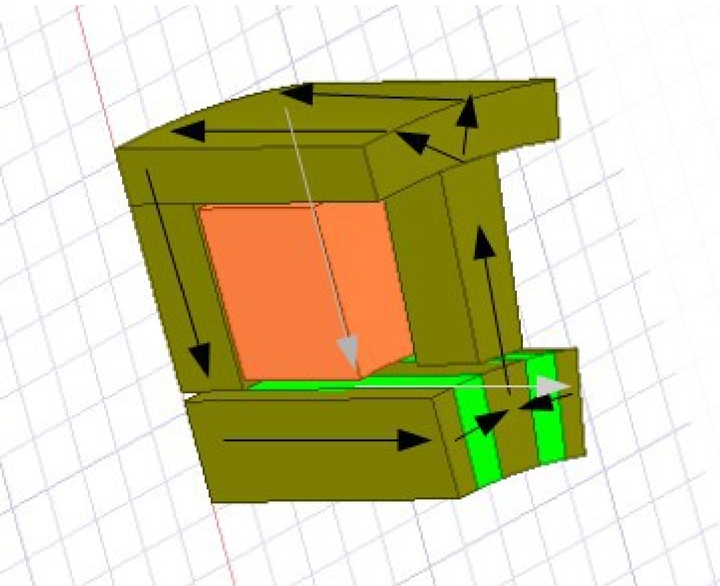


Figure 3. Main flux parts.

Furthermore several leakage parts are present and adds leakage flux to the main. Figure 4 shows the leakage in the winding part and across the magnets.

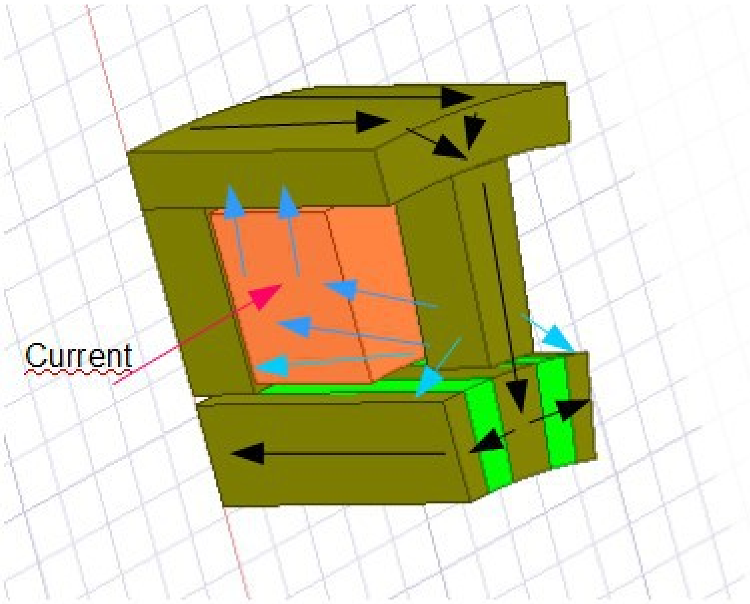


Figure 4. Leakage flux parts.

The machine has as a start the following data:

Outer radius, ry	100 mm
Core inner radius, r3	95.5 mm
Tooth axial length, lfe	8 mm
Stator inner radius	77 mm
Axial length winding	13 mm
Insulation thickness	0.5 mm
Magnet radial thickness, hm	10 mm
Magnet angular	2.5 grad
Number of poles	48
Air gap delta	1 mm
Nominal speed	4000 rpm
Number of turns in the winding	22

3. 3D-model and inductance model on Machine #1

The machine are analysed using the Maxwell FEM-program.

From the model it is found:

Ifas (Arms)	Torque (Nm)	ψ (Wbpeak)
0	0	0.0174
40	10,3	0.0241
80	20,2	0.0394
120	27,5	0.0506
160	32,2	0.0598

At 160 A the flux density in the tooth is very high which limits the performance. The flux density in other parts are lower than 1.3 T.

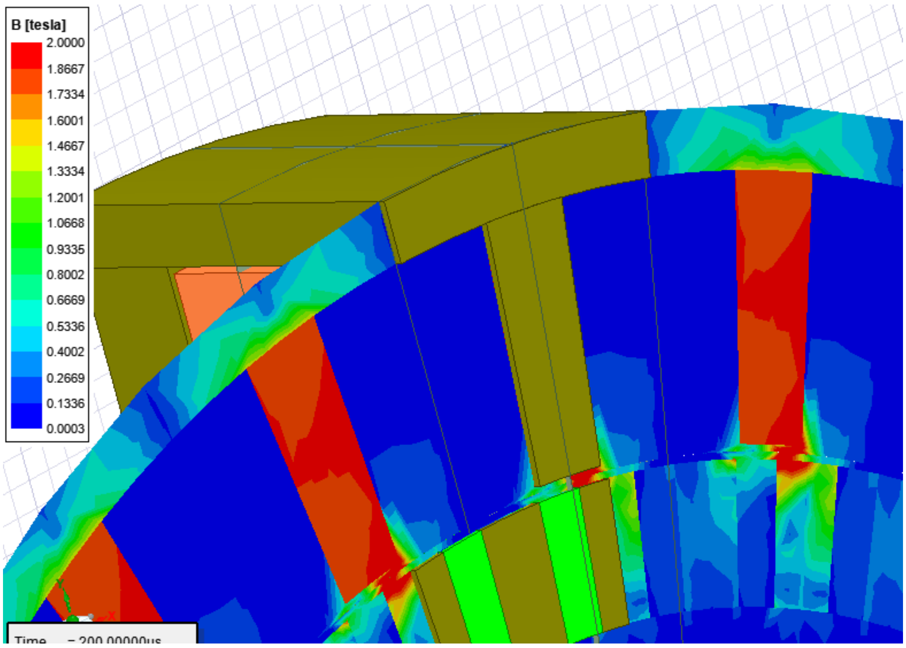


Figure 5. Cross section of the tooth at 160 A.

The high flux in the tooth is due to high armature reaction and the produced flux means a too high flux density in this part.

The flux are identified at 80 Arms before the machine starts to be nonlinear.

Ifas (Arms)	Torque (Nm) One stator	P (Wbpeak)
0	0	0.0174

i_q=80	20,2	0.0394
i_d=80	0	0.0487
i_d=-80	0	-0.0241

Based on the flux we can conclude:

Psim=0.0174 Wb

L_{d+}=277 uH positive id

L_{d-}=367 uH negative id

L_q=625 uH

At i_q=80 A the FEM-calculaed torque is 20.2 Nm and when using the inductance values the torque result is 23.6 Nm for one stator phase. It can be seen that a positive i_d has lower impact on the flux than the negative current, $L_{d+} < L_{d-}$.

5. Machine #2

When increasing the tooth axial width parameter l_{fe} to 16 mm, higher flux can be used without saturation but eventually the rotor becomes saturated as well. Of that reason h_m is increased to 12 mm. The flux from the winding is higher than the flux from the magnet which is a problem. To solve this the current loading could be lowered but also an increase of the magnet could work as well. So the remanent flux density of the magnet is increased to 1.0 T and the number of turns in the winding is lowered to 9. The result is T=80 Nm per phase at 250 A, which corresponds to the three phase torque of 240 Nm.

Ifas (Arms)	Torque (Nm)	P (Wbpeak)
0	0	0.0223
50	16,3	0.0224
100	34	0.0229
150	51,2	0.0272
200	67,6	0.0322
250	82,6	0.0379

Flux through the winding is identified to

Ifas (Arms)	Torque (Nm)	P (Wbpeak)	Psimodell

	One stator		
0		0.0223	0.027
i_q=125	41	0.0248	
i_d=125	0	0.0334	0.047
i_d=-125		0.0047	

Based on the flux we can conclude:

Psim=0.0223 Wb (U=273 Vrms @4000 rpm)

L_{d+}=62.8 uH

L_{d-}=99.6 uH

L_q=61 uH

The losses at 4000 rpm and 249 Nm(three phases) are:

Pcu=588 W

Pfe=6 kW

The losses are quite high and especially the core losses are a problem in vehicle operation where the torque is low during most of the operation. This means a high core loss will result in poor efficiency at low load.

The mass of the machine is:

mfe (stator) = 5.0 kg

mcu=1.3 kg

mfe (rotor) = 4.2 kg

mNd=2.1 kg

Total weight of active material 13. kg.

6. Reluctance model

In order to find a tool that could be used to optimise the machine without solving 3D-FEM for each iteration a reluctance model is developed. The model uses linear parameters and loss of flux has to be estimated.

$$R = \frac{F}{\varphi}$$
$$F : electromotive\ force(A)$$
$$\varphi : flux\ (Wb)$$

$$R = \frac{l}{\mu_r \mu_0 A}$$
$$\mu_0 : permeability$$
$$l : lenght\ of\ object\ (m)\ A : cross\ sectional\ area\ (m^2)$$

using this, the reluctance of different parts are calculated to:

		Value
Air gap	Rd	8.22e6
Tooth(assuming ur=1000)	R1	1.52e5
Back iron core	R2	7.06e5
Rotor tooth	R3	1.66e5
Magnet	Rm	4.83e6
Magnet force	Fm	2667 A
Winding	Na * I	3535 At
Leakage winding	R4	
Leakage pole surface	R5	
Leakage magnet	R6	10% of flux

This model misses a lot and overestimates(20-30 %) the magnet flux as well as the flux from the winding. It will need a lot of tuning to get it in the same range and perhaps it's not a valid tool for the dimensioning. Corners of the stator and rotor teeth will saturate which is hard to model in this way so it is not recomended as evaluating tool. It could eventually be used for smaller changes of the dimensions when a near optimal pole is found.

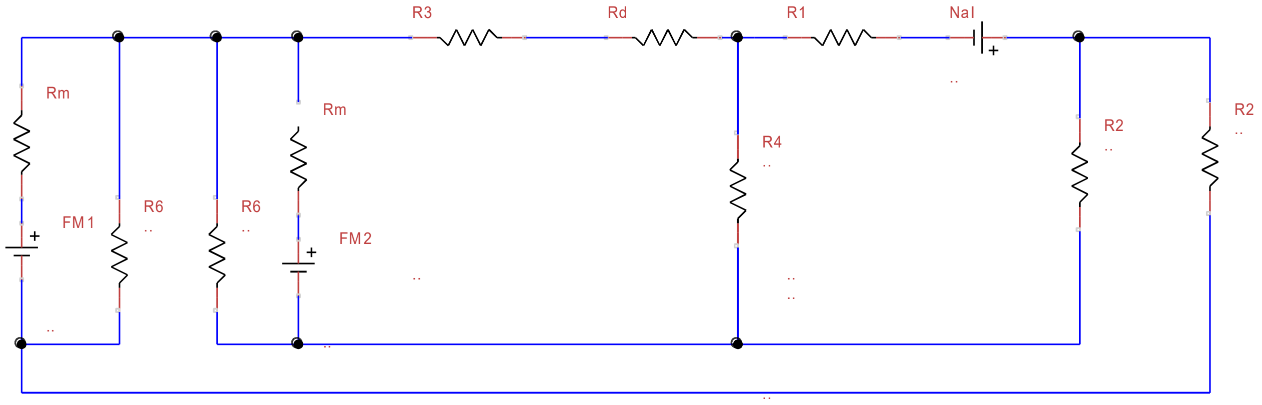


Figure. 6 Reluctance model of pole.

7. Machine #3

The previous machine has very high core losses at 240 Nm and 4000 rpm. When increasing the air gap diameter the winding area are lowered and the volume of the tooth is also lowered. I.e. the copper losses will increase and the core losses will decrease. The third motor have the following data:

T=241.5 Nm 4000 rpm, Iq = 240 A

mcu=1,1 kg (Jcu=20 A / mm2, kcu=0.7)

mNd=2.4 kg

mFerot=3.7 kg

mfestat=4.03 kg

Total mass active material 11.2 kg

P_{cu}=588 W

P_{fe}=3140 W

At 0 current

P_{cu}=0

P_{fe}=1703 W

At zero flux (field weakening)

i_d = -180 A

P_{fe}= 270 W

P_{cu}=1080 W

At 54 Nm and 4000 rpm

P_{fe}=1733 W

P_{cu}=24 W

Dimensions of Machine #3

Outer radius, ry	100 mm
Core inner radius, r3	95.5 mm
Tooth axial length, lfe	16 mm
Axial length winding	13 mm
Stator inner radius	86 mm
Insulation thickness	0.5 mm
Magnet radial thickness, hm	12 mm
Magnet angular	3 grad
Number of poles	48
Air gap delta	1 mm
Nominal speed	4000 rpm
Number of turns in the winding	9

This latter machine has the possibility to be used as a traction motor. The armature reaction is in the right range but the core losses are to high compared to the radial flux machine. The magnet weight is also quite high so there are still several iterations before a viable solution is at hand.

As a comparison to other machines from [6]

Radial flux machine 24 kg

Axial flux machine 10 kg

The axial flux machine has low weight but has also low efficiency during the drive cycles.

8. Winding

A winding to this machine type can easily be produced using sheets of copper. The sheets could be made as a simple toroidal structure. There is however a problem when increasing the frequency and that is proximity and skin effect. For instance at 1000 Hz the skin depth is 2.1 mm. This means that a sheet with the width of 15 mm, will use 2 mm at the edges for conduction of the current.

An alternative is to use parallell branches of smaller conductors that alter position during the winding process. Changing positions for instance each turn will need some space and that lowers the fill factor of the winding.

9. Future work

Future work could be to find a better solution for cars with lower core losses and perhaps even lower weight. Map all operating points and compare it to other solutions as in [6]. The high iron core losses are a problem but changes towards lower core losses and higher winding losses may be possible. In light vehicle applications the core losses at low torque are important. The most operational points are at quite low torque and medium to high speed so the core losses are vital.

I think the machine could be useful in aircrafts, low weight and perhaps the torque ripple and core losses could be tolerable in such an application.

The iron core material is a problem with high losses and finding a solution to this is of mayor interest. The calculation has also to be refined as the hysteresis losses of the calculation model is not stable. The cooling of the winding and perhaps the rotor has to be looked into.

One important issue is the losses in the material and how this will develop in the future.

Another interesting topic is the winding where two extreme can be seen. In one end a spiral of copper sheet and in the other end the winding is made of Litz wire.

Cooling is of course an issue when we are looking into high performing machines. The iron powder material has low thermal conductivity and some different solutions can be seen. Liquid cooling directly in the winding is one option and another one is potting with a high thermally conducting potting material.

10. References

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