

3D-FEM Simulation of a Transverse Flux Machine Respecting Nonlinear and Anisotropic Materials

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Abstract: This paper presents the three dimensional (3D) Finite Element Method (FEM) COMSOL model of a Three Phase Permanent Magnetic Excited Transverse Flux Machine (TFM). The model is fully parameterized and able to sweep over all parameters during design optimization process. The nonlinear BH curve of stator and rotor material as well as the anisotropy of the laminated rotor stack is considered. In order to reduce simulation time and computation effort model symmetries are respected and a mixed formulation with vector and scalar potential is used.

Keywords: Electric Machines, AC/DC Module, Rotating Machinery, Transverse Flux Machine, 3D Model, Anisotropic Nonlinear Material, Mixed Formulation.

1. Introduction

In the last years, computation hardware became more and more powerful and affordable and made FEM modeling one of the most common tools in designing and optimizing electrical machines.

Electric Machines in general and the Transverse Flux Machine with its 3D flux conduction in particular have some difficulties in accurate and correct modelling for numeric computations.

The often quite complex geometry has to be modeled and small dimensions like the air gap and tooth geometry can coincide with large outer dimensions. Furthermore, the air gap should have a quite fine and ideally quadrilateral or hexahedral mesh for best torque computation. This increases element number and computation time and limits the number of parameter variations, which can be investigated during the design optimization.

The nonlinear behavior of the soft magnetic materials, especially in modern highly utilized magnetic circuits has to be considered. Also, iron losses are often not negligible.

Complex shaped coils in various electric connections with nontrivial excitation (for example with a pulse width modulation from an inverter) have to be modeled adequately to obtain important key data like the machine's back-EMF and torque production. Therefore, the relative motion of the rotor and stator has to be modeled.

Finally, electric machines are in general multiphysic problems with couplings between the electric, thermal and mechanical model.

2. Transverse Flux Machines

The Transverse Flux Machine (TFM) works in principle like a Permanent Magnetic Excited Synchronous Machine (PMSM), with the difference, that not the three phase magnetic fields superpose in the air gap, but the three phase torques mechanically superpose to the total shaft torque. Beside from that, each phase is assumed to be magnetically decoupled from the other phases with its own magnetic circuit and can therefore be regarded separately.

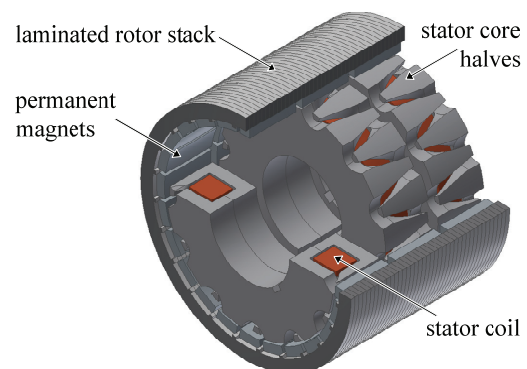


Figure 1. 3D model of the three phase transverse flux machine [1, 2]

Each phase consists of a ring winding and a soft magnetic circuit that guides the magnetic flux 3D around this ring. In contrast to PMSMs, the cross sectional areas of flux and current guiding parts do not compete for available space as in TFMs they are perpendicular to each other.

This enables a significant increase of the number of pole pairs leading to a higher torque density. With the rise of the pole number also the fundamental stator frequency increases and in consequence also the frequency dependent iron losses. Therefore, this type of machine is most suitable for applications with low rotational speed, but high torque demand.

In order to realize the required 3D magnetic flux guidance, a soft magnetic material with isotropic permeability (for example Soft Magnetic Composite (SMC)) or a special construction with laminated stacks is used in stator and/or rotor [3].

The TFM regarded in this paper is shown in Figure 1. It has an external rotor consisting of an axial laminated stack consisting of non-grainoriented laminated steel sheets with surface mounted NdFeB permanent magnets. The machine has three 120° electrically shifted stator phases. Each stator phase consists of two stator core halves made from SMC material, which are assumed to be magnetically anisotropic. The machine has an inner diameter of 20 mm, an outer diameter of 53 mm and 12 pole pairs.

3. Building the Computer-Aided Design

Assuming perfect symmetry and total magnet decoupling of the three phases, only one pole pair of one phase has to be modeled. The CAD model is shown in Figure 2.

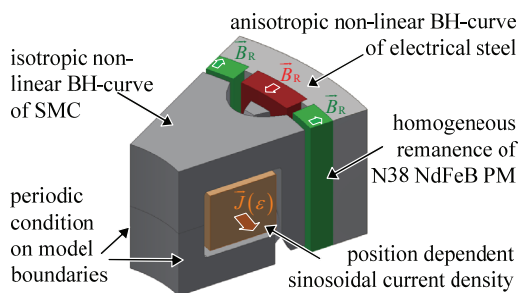


Figure 2. FEM model of one pole pair of one phase

The computer-aided design (CAD) of the complex geometry is outsourced to Autodesk Inventor 2016 and imported with the “LiveLink™” to COMSOL 5.2. This allows COMSOL to manipulate CAD parameters during the optimization process and get the corresponding design to a given parameter set from Inventor automatically.

In order to obtain only feasible designs, a master drawing has been set up in Inventor, holding all parameters. All components are derived from this drawing. The machine design is an assembly of all these components, whose parameters are also derived from the master drawing. The parameter interdependencies between free and driven parameters are managed in COMSOL by defining the driven parameters as a function of the free ones.

For using the rotating machinery with its prescribed rotation feature, rotor and stator are defined as separate unions and formed to an assembly in COMSOL. On the contact surface an identity pair is automatically created.

4. Materials

For setting up the FEM model, several material definitions are used as shown in Figure 2. The air is not visible in Figure 2 and modeled like a wedge. In the middle a cylinder is subtracted (see Figure 9).

The material data of air and copper are copied from the COMSOL material database. The conductivity of air is redefined to 10 S/m because to receive a stable solution.

The material data used is shown in Table 1. In this paper only stationary studies are solved. Therefore no eddy currents are considered and the conductivity of SMC is set to the same than air.

Table 1: Material data

stator	symbol	value
SMC	-	SIRON® S300b
maximum magnetic permeability	$\mu_{r,max}$	312
flux density @10 kA/m	$B(10\text{kA/m})$	1.52 T
Electrical conductivity	σ	10 S/m
PM		
NdFeB grade	-	N38 SH
coercitivity @20 °C	$H_{c,B}$	965 kA/m
remanence @20 °C	B_r	1.26 T
magnetic permeability @20 °C	μ_r	1.05

rotor		
electrical steel	-	M270-35A
maximum magnetic permeability	$\mu_{r,max}$	6175
stacking factor	k_{Fe}	95%
flux density @10 kA/m	$B(10kA/m)$	1.8 T

4.1. Soft Magnetic Composite

The nonlinear B(H) curve for SMC is shown in Figure 3. Typically, SMC saturates at high magnetic field. The manufacturer's data is extrapolated manually to stabilize the nonlinear solver (red points in Figure 3). To speed up the nonlinear solver, interpolation is set to "piecewise cubic" and extrapolation to "linear"[4].

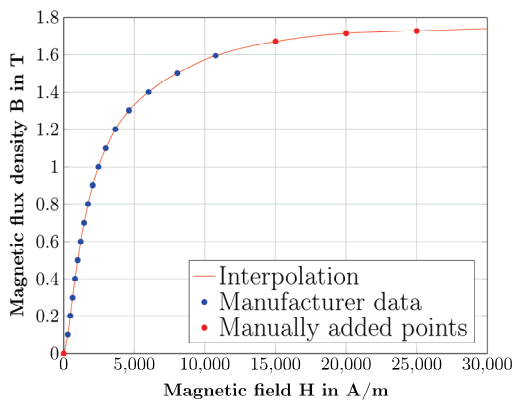


Figure 3. Commutating curve of SMC

4.3 Laminated Steel

Laminated steel is used to reduce the eddy current losses. A principle construction of laminated steel is shown in Figure 4.

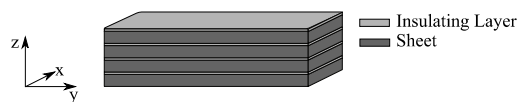


Figure 4. Stack of laminated steel sheets

Between every single sheet there is a thin insulating layer with low conductivity and low permeability. This offers high permeability along the lamination, but has low permeability

perpendicular to the lamination. This behavior has to be considered without modeling every single sheet which would lead to very small elements and increase the total number of degrees of freedom massively.

This is why an effective homogenous material showing the same macroscopic behavior like the laminated stack is deduced.

First, the material without lamination is regarded in a homogenous magnetic field. Figure 5 shows a piece of solid steel and its magnetic equivalent circuit (MEC). Ampere's law and the constitutive material relation can be simplified to

$$\Theta = H \cdot l$$

$$B = \mu_0 \mu_r H.$$

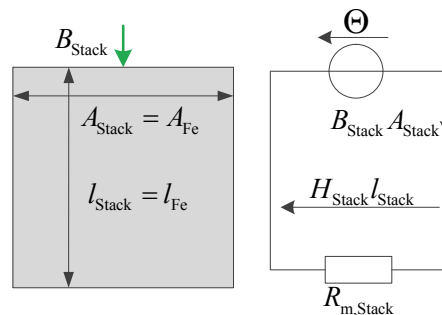


Figure 5. Solid material and related MEC

In Figure 6, flux is entering parallel to the lamination. Also the related MEC is shown. The stacking factor k_{Fe} is defined as $k_{Fe} = \frac{A_{Fe}}{A_{Stack}}$.

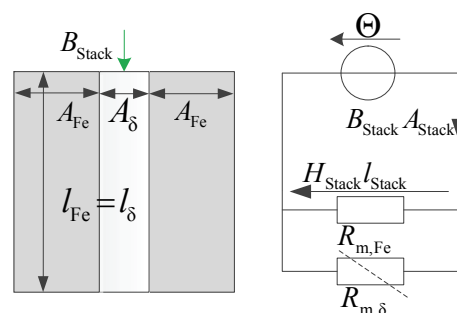


Figure 6. Flux parallel to lamination and related MEC

The magnetic reluctance of air $R_{m,\delta}$ is parallel to the magnetic reluctance of iron $R_{m,Fe}$ and $R_{m,\delta} \ll R_{m,Fe}$. Therefore, $R_{m,\delta}$ is neglected.

As a result, the lamination will reduce the effective cross sectional area conducting magnetic flux. The homogenized material has a slightly smaller effective permeability and can be calculated to

$$\begin{aligned}\mu_{r,\text{parallel}} &= k_{\text{Fe}}\mu_{r,\text{Fe}} \\ H_{\text{Stack}} &= H_{\text{Fe}} \\ B_{\text{Stack}} &= \mu_0\mu_{r,\text{parallel}}(H_{\text{Fe}})H_{\text{Fe}}.\end{aligned}$$

In **Figure 7**, flux is entering perpendicular to the lamination. In this case the stacking factor k_{Fe} has an impact on the iron path length:

$$k_{\text{Fe}} = \frac{l_{\text{Fe}}}{l_{\text{Stack}}}.$$

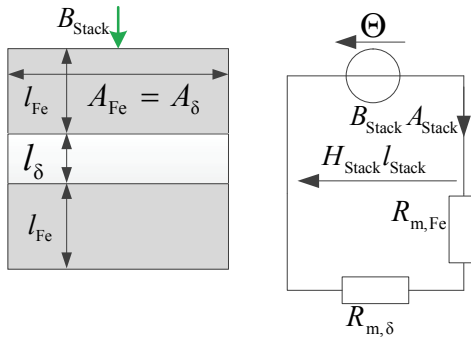


Figure 7. Flux perpendicular to lamination and related MEC

Here, $R_{m,\delta}$ is in series with $R_{m,\text{Fe}}$. Therefore, it has a huge impact on the total reluctance. Due to all these little air gaps the homogenized material has a nearly linear and much smaller effective permeability. It can be derived to

$$\begin{aligned}\mu_{r,\text{perpendicular}} &= \frac{\mu_{r,\text{Fe}}}{\mu_{r,\text{Fe}}(1 - k_{\text{Fe}}) + k_{\text{Fe}}} \\ H_{\text{Stack}} &= \frac{B_{\text{Fe}}}{\mu_0\mu_{r,\text{perpendicular}}(B_{\text{Fe}})} \\ B_{\text{Stack}} &= B_{\text{Fe}}.\end{aligned}$$

The $B(H)$ curves for steel without lamination and laminated steel with magnetic flux parallel and perpendicular to lamination are shown in **Figure 8**.

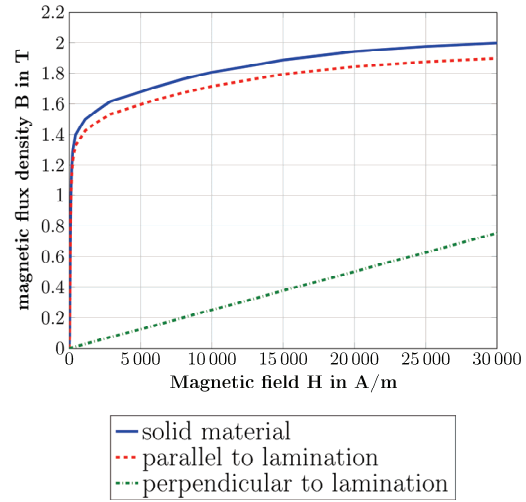


Figure 8. Commutating curves of steel

In COMSOL the nonlinear anisotropic material is modeled using anisotropic permeability. The permeability is defined as a tensor inserting nonlinear permeabilities as proposed previously.

5. Problem definition

The “rotational machines magnetic” physic is used. This allows using magnetic scalar and vectoring potential which minimizes the number of degrees of freedom. It is combination of the physic “magnetic fields without current” and “magnetic fields”.

The equations solved for are for vector potential formulation (“Ampere’s law”)

$$\nabla \times H = J$$

$$B = \nabla \times A$$

and for scalar potential formulation

(“Magnetic flux conservation”)

$$H = -\nabla V_m$$

$$\nabla \cdot B = 0.$$

The scalar potential is used for the PMs, laminated steel and the air gap. The vector potential is used for the coil, SMC and the air between them (see **Figure 9**).

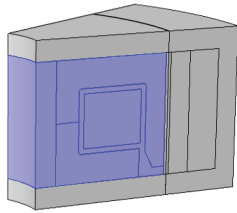


Figure 9. Domains with vector potential (blue) and scalar potential (gray)

It is recommendable that both potential formulations touch a model border without a periodic or symmetry constraint. Therefore the air is not modeled as a complete wedge.

The “Force Calculation” node is used to calculate the torque selecting all none air rotor parts for evaluation.

On the contact area of the two SMC core halves will be a thin air gap. This is modeled using “thin low permeability gap”.

The ring winding can be modeled by an “external current density”. The electrical conductivity is defined as a tensor in cylinder coordinates with high conductivity only in tangential direction. The current form is sinusoidal and has its maximum at 90° electrical rotor position. This is equivalent to zero d-axis current.

As shown in Figure 2 only one pole pair of one phase is modeled to reduce the total number of degrees of freedom. For modeling the complete machine behavior periodic conditions are set. There is one periodic condition for rotor and one for stator. Furthermore, the identity pair is described as “sector symmetry”. The number of sectors is the same as the number of pole pairs.

The scalar potential is gauged by setting a zero potential at one point outside the rotor in the air. For gauging the vector potential “Gauge Fixing for A-Field” is used and “Ensure constraint on value” is enabled.

It has turned out that using linear discretization with finer elements is more stable for this type of problem than less elements with quadratic discretization.

The mesh is very fine in the air gap and is getting coarser away from it. At the “Periodic Condition” one surface is meshed and copied to the other. For the first steps of optimization a coarse mesh is used and set finer for a better solution at the last steps.

In the last steps, the complete model has about 1.7 million elements with 7 layers along the air gap and an average element quality of 0.75. Figure 10 shows the histogram of the element quality for the entire geometry.

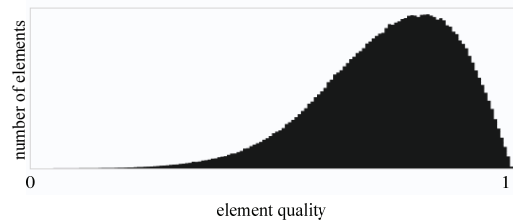


Figure 10. Element quality histogram for entire geometry

6. Solver

A direct stationary solver (MUMPS) is used. The rotation of the motor is modeled with an auxiliary sweep over selected rotor positions. This enforces mesh generation only once for each geometry. The option “Run continuation for:” is disabled and “Reuse solution from previous step” is selected to speed up nonlinear solving.

For solving the nonlinear problem the Newton method is chosen. Due to high nonlinearity a linear presolving for the first position is added. Its solution is used as initial value for the nonlinear solver. The permeability for laminated steel and SMC in the linear step is set to an average permeability obtained by previous simulations.

With the finest mesh, the computation time is about 1h 10min for 19 rotor positions. The number of degrees of freedom is more than 670000. The solver needs about 82 linear solutions, which means 4.3 linear steps for the nonlinear solver at each position. About 13.5 GB memory is needed and a personal computer with an Intel Core i7 with eight 3.4GHz logical cores is used.

7. Results

Figure 11 shows the result of the magnetic flux density distribution at rotor position $90^\circ / z_p = 7.5^\circ$ as color surface. In red arrows the direction of the magnetic flux and in black

arrows the direction of the external current density is plotted.

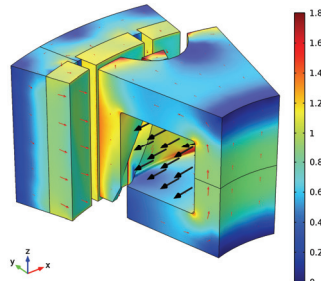


Figure 11. Absolute magnetic flux density in T, flux direction (red) and current direction (black), $\varepsilon_{el} = 90^\circ$

The most important target during optimization is the three phase torque. The torque of one single phase is calculated by multiplying the torque of one pole pair of one phase with the number of pole pairs. The three phase torque is calculated in post processing by superposing the single phase torque three times, each 120° electrically shifted. **Figure 12** shows the comparison of the simulated and measured three phase torque dependent on provided current amplitude.

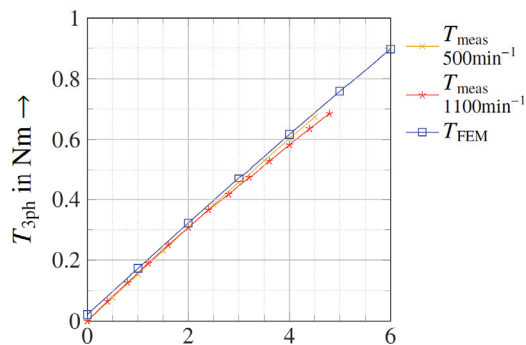


Figure 12. Comparison of measured and simulated three phase torque

Simulated and measured torque match very well although iron losses are neglected in simulation. Optimization algorithm [1] increased the torque density by 20% and decreased torque ripple by 80%.

8. Conclusions

This paper outlines the three dimensional CAD and FEM design of a permanent magnetic transverse flux machine. The modelling of

laminated steel with anisotropy and nonlinear permeability is in detail discussed.

Furthermore the procedure for fast solving the nonlinear behavior and the rotation is presented.

The model is built as a parametrized model for use in an optimization process [1].

Measurements and simulation match very well.

9. References

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