Expert System for Synchronous Machines Based on COMSOL Multiphysics

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Abstract: EaSync is a growing semiautomatic engineering tool for simulating and designing synchronous machines. This Paper focuses on the Optimization module, which is based on the FEA program COMSOL Multiphysics® and is connected through COMSOL LiveLink™ and controlled by MATLAB® and the MATLAB® Optimization Toolbox. The structure and the capabilities of EaSync are presented and the calculation of the cogging torque is compared to measuring. Techniques for improving the measuring of cogging are discussed.

Keywords: synchronous machine, cogging, optimization, automated preprocessing

1. Introduction

Due to the increasing interest for effective actuators the synchronous machine is often the solution that combines high efficiency and high power density. This can be especially observed in the automotive industry, where beside the combustion engine more and more actuators are replaced. One example is the electric power steering. This mechatronic system uses a synchronous machine to reduce the needed torque at the steering wheel. It is replacing the hydraulic steering system which is fixed connected to the motor and misses the energy efficiency and dynamic of the new approach. The driver is able to steer the car with even less exertion and gets a better feedback from the steering wheel. But when it comes to direct interaction between actuators and the driver other than that mentioned properties must be satisfied. Especially the cogging torque of the synchronous machine can be an unsettling effect for the driver. This torque derives from the interaction of the permanent magnets with the pole pieces in the stator.

Even though the researches in synchronous machines are advanced, the practical design still is a problem because of the complex interaction between several design parameters. The project "EaSync" at the Ostfalia University focuses on the bundling of synchronous machine models to create a semi-automatic engineering process using COMSOL Multiphysics® and MATLAB® as programming language. The project is based on student research projects at the Ostfalia University.

As the engineering process of EaSync is mainly based on finite element analysis (FEA) results, it is essentially important to assure, that this part of the tool chain functions properly. FEA is used to find an approximate solution for differential equations discretizing the observed area. In this case the Maxwell Equations are solved to define the characteristics of synchronous machines. The crucial part of FEA is the preprocessing. This process is described and approaches to improve the calculation of cogging torque are discussed.

2. Structure and capabilities of EaSync

The structure of EaSync is shown in Fig. 1. The central element is COMSOL LiveLink™ which is used to couple COMSOL Multiphysics®, MATLAB®, MATLAB® Simulink, MATLAB® Optimization Toolbox and the Graphical User Interface (GUI).
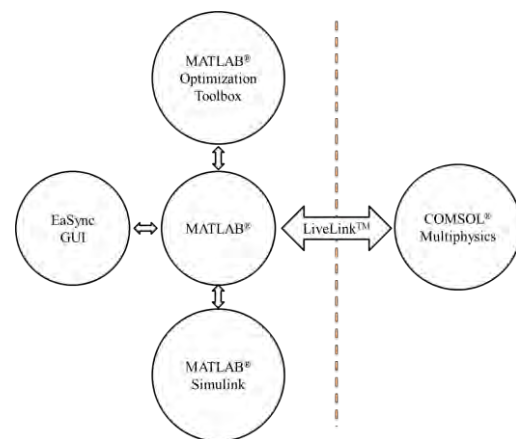

Figure 1 Structure of EaSync

The user interacts via a Graphical User Interface (GUI) with EaSync and is able to access all modules and combine their features. This leads to short modeling process. It is possible to run analytic models based on

parameters which are calculated with FEA and vice versa without porting manually data between programs. Additionally the user obtains access to the optimization algorithms of MATLAB®. Two examples show, how the user obtains advantages using COMSOL LiveLink™ comparing to a solitary FEA and MATLAB® solution. To proof the functionality of EaSync an existing motor design was used to compare results. It is a small sized synchronous machine with permanent magnets and a maximum output power of 100 W. The geometry is given by a CAD-File but is implemented using the parametric geometry builder included in EaSync. The data is resumed in Tab. 1. The machine has no surface mounted magnets instead a hollow cylinder technique is applied (Fig. 2).

Figure 2 Synchronous machine (DUT)

rated power	100.5W
rated voltage	up to 3~400V
rated speed	1500rpm at 50Hz
rated torque	0.64Nm
rated current	228mA
winding type	tooth-coil technology
number of poles	4
number of slots	6

Table 1 Properties of the synchronous machine

For the first example a common task for mechatronic or system engineers was selected. It is the design of an actuator concept including the control, the power stage and the motor itself. In a very early state of the motor design a parallel design of the control and power stage unit is desired, as shorted development times are usual for contemporary projects. Two adequate tools to achieve this are MiL (Modell in the Loop) and HiL (Hardware in the Loop). In place of waiting for

a final motor design a model of the motor is used instead of real hardware to design the control and the power stage. Motor, control and power stage or even more parts of the complete system are designed at the same time. Changes in the motor design require changes in the motor model and changes in the system design can change the motor specifications. This leads to a repetitive work designing the motor and deriving new models for the system design (Fig.3).
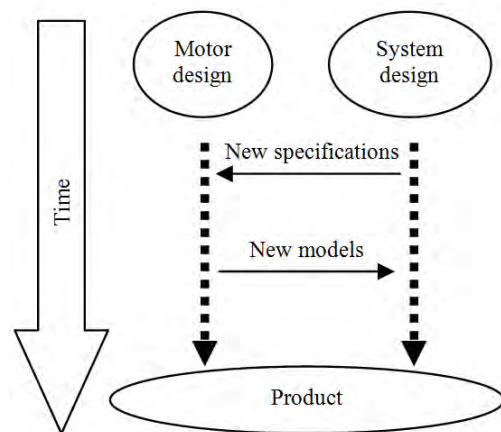

Figure 3 Designing process

EaSync is capable of deriving a whole set of machine parameters using COMSOL LiveLink™ and MATLAB® as programming language. The process is started by one command and is fully automated. This process includes the simulation of cogging torque, Back E.M.F and magnetic reluctances for d- and q-axis. With this set of parameters a Simulink model is generated which allows a transient analysis of the machine and can be used to design other components that are dependent of the motor design. Figure 4 shows the process and the involved software tools. First of all the geometric data of the motor must be given, as this example is not a designing process but a model being created. The data is used to run the geometry builder which controls COMSOL Multiphysics® over MATLAB®. The geometry builder is based on predefined machine types. At the current state EaSync is capable of building machines with surface mounted magnets and internal rotor. The building process begins with one pole and one slot. Afterwards the number of pole pairs and the number of slots is used to copy the elementary geometric entities. This is done fully automated and concerning interferences between geometric objects. Then the winding

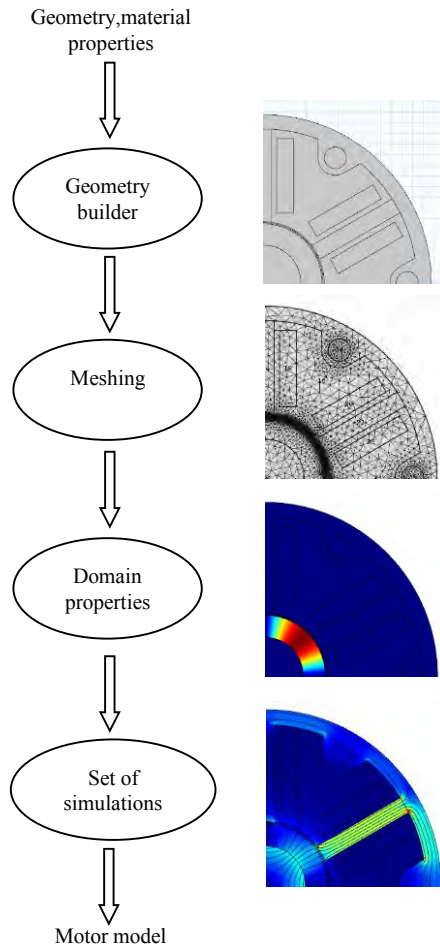areas are added and the geometry is ready to be meshed.

Geometry,material
properties

Geometry
builder

Meshing

Domain
properties

Set of
simulations

Motor model

Figure 4 Modeling process using EaSync

The automated meshing process is possible because of the high flexibility and reliability of the mesh generator in COMSOL Multiphysics 4.2. Especially the air gap is a critical area for meshing. That is why the meshing process starts there. If possible a structured mesh with rectangular elements is added to the air gap. This is only possible if the rotor or the stator have nearly cylindric geometries, otherwise a different meshing strategy is chosen and a hybrid mesh consisting of quadratic and triangle elements is applied.
Subsequently the winding and magnetic properties are associated to domains. Finally a set of simulations are done. In this case a transient analysis with rotating rotor and without currents leads to the Back E.M.F and the cogging torque. By adding currents the reluctance is defined. Ripple torque

calculations are also possible. This process happens fully automated.
The results are compared in Tab. 2 to the measuring. Simulation results and measured data accord in periodicity but have unequal amplitudes (Fig. 5.). Typical for the cogging torque calculation is the smaller amplitude in the simulation. This effect derives from the simulation being done with idealized magnetization and geometry data. Additionally the magnetization properties were given by the motor manufacturer and not verified by the new measuring rig being built at the Ostfalia University.

	Simulation	Measuring
Induced voltage at 1500 rpm	410V	400V
Inductance Ld and Lq	0.8H-0.9H	1H
nominal torque	0.75Nm	0.64Nm
cogging torque	0.007Nm	~0.020Nm

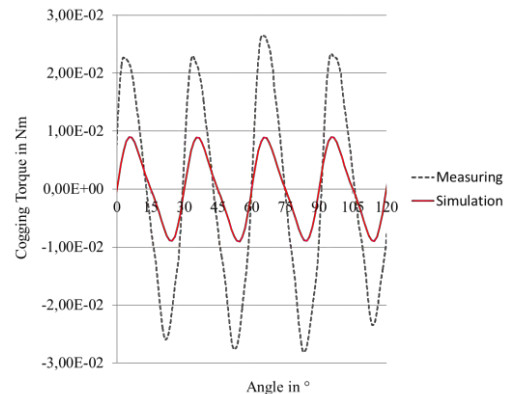**Table 2** Comparing simulation and measuring

Figure 5 Comparing the cogging torque

The results can also be ported into a Simulink model based on a field-oriented control to simulate transient characteristics of the machine and design control algorithms.
The second example is an optimization process concerning the pole width of the existing machine. This example couples the MATLAB® Optimization Toolbox with COMSOL Multiphysics®. As optimization processes are based on iterations lean models are important. EaSync is capable of reducing computing time by bending the geometry and detecting symmetries (Fig. 6). This reduces the model up to the width of one pole [2].
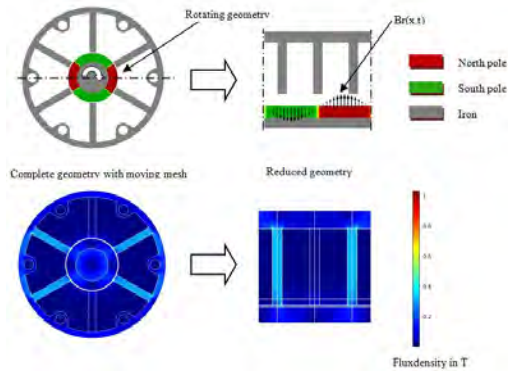
Figure 6 Reducing the model

Just before the optimization parameter(s) converge(s) to an optimum the complete and not bended model is used to find an exact solution. In this case Fig. 7 shows that the reduced model leads to a very similar result and is consistent to the actual pole width chosen by the manufacturer. Figure 7 also explains the difference between calculated and measured cogging torque. This is because of the strong gradients near the optimum. A variation of 5% around the chosen magnetization width is typical for the analyzed machine.
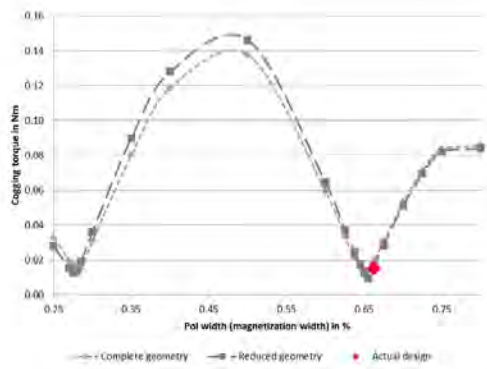

Figure 7 Comparing the full and the reduced model

3. Improving the calculation of cogging torque

Cogging torque derives from the change of magnetic energy stored in a synchronous machine due to the permanent magnets. A wrong calculation of cogging torque is compared to two correct calculations in Fig. 8. The first indicator for a wrong cogging torque calculation is an offset. A correct calculated cogging torque has no offset, as after one period no energy is stored in the system and no energy is taken out of the system due to the rotation. A constant component of torque is in conflict to that, as the integration over one period would not be zero. Beside the offset the missing of periodicity or symmetry are indicators. Both effects derive from improper meshing in the air gap or inadequate calculation methods concerning the torque and the shape functions of the elements.

When it comes to the calculation of cogging torque two approaches are usually chosen. One approach is based on the magnetic energy stored in the motor. The change of magnetic energy causes a torque which can be expressed by equation (1) [1]. W_{mag} is the integral of the magnetic energy density over the whole model (also called magnetic co-energy), while α is the rotation between two calculation steps. The variable l defines the effective length of the rotor.

$$T_W = l\frac{\mathrm{d}W_{mag}}{\mathrm{d}\alpha} \qquad (1)$$

The alternative is based on the Maxwell Stress Tensor which is integrated along a contour (in 2D models) to compute forces and torques. Unfortunately COMSOL Multiphysics® does not calculate reasonable torques with the first method when permanent magnets are used. This behavior is known by the software engineers of COMSOL Multiphysics® and hopefully a future patch will solve this problem. Till then EaSync is limited to the Maxwell Stress Tensor. This is a disadvantage as the integration of the Maxwell Stress Tensor leads to numerical errors especially when handling severe gradients along the contour. This can be shown by calculating the torque on the stator and on the rotor of the given motor design. In Fig. 2 the rotor is totally cylindrical while the stator has slots for the windings. The results of both calculations are compared in Fig.7. Against physical correctness the torques are different. This conclusion leads to the first rule concerning force calculations. EaSync chooses the more cylindrical contour to calculate forces and torques to reduce the path of integration. This reduces numerical errors.
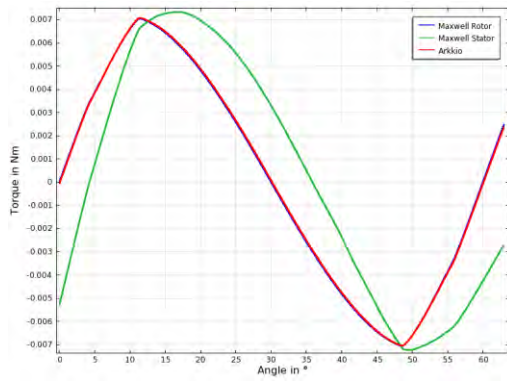
Figure 8 Different torque calculation approaches

The second method to improve the calculation of torques is the type of mesh elements used in the air gap. The most common element type in 2D FEA is the first order triangular element. This kind of elements are defined trough three nodes and constant gradients along the lines concerning the magnetic vector potential A_Z (2), where p_0 to p_2 are the variables solved for.

$$A_z(x,y) \sim p_o + p_1 x + p_2 y \qquad (2)$$

Within the triangular element the flux density is constant (1).

$$B(x,y,z) \sim (p_2; p_1; 0) \qquad (3)$$

A typical orientation for a few triangular elements in an air gap is shown in Fig. 9. Due to the slots in the stator the flux is not radial oriented at every point of the air gap. The bending of the field is expressed by linear elements. The discretization is inadequate and the field does not leave the stator orthogonal. Due to the permeability difference between air and iron an angle of 90° is physically correct. An integration of the x and y components of this deformed field distribution using the Maxwell Stress Tensor leads to imprecise solutions concerning forces but especially torques because of the wrong direction. First order rectangular elements have also constant gradients between their nodes but not necessarily a constant flux density in the element. A linear variation is possible. This makes rectangular elements more suited for air gaps with low number of elements in radial direction. This advantage is also kept, when quadratic discretization is used in the model.

With growing number of elements in the air gap the mentioned characteristics are attenuated and the rectangular elements lose their advantage.
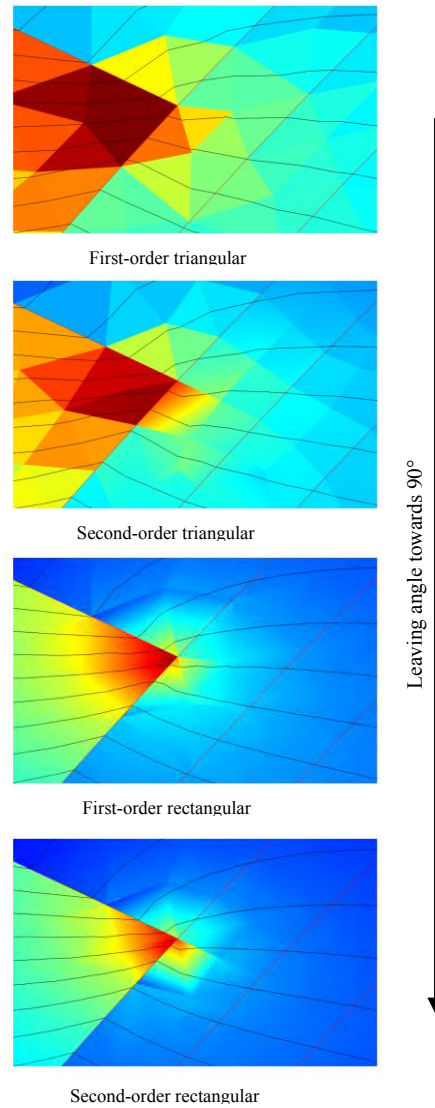

First-order triangular

Second-order triangular

First-order rectangular

Second-order rectangular

Leaving angle towards 90°

Figure 9 Leaving angle of the magnetic field

But as the number of elements affects the meshing and computing time an optimized mesh is a crucial for an effective engineering tool. Additionally a big number of linear elements lead to interface errors [3].

Geometries can be very complex and sometimes triangular elements are the only chance to generate a mesh suiting the complex contours. To face the mentioned problems two approaches are used. The first approach is based on a single layer of rectangular elements in the air gap combined with triangular elements (hybrid mesh). This approach combines the flexibility of the rectangular meshes concerning the representation of the

field but also the flexibility of the triangular elements to adept to contours. The mesh is kept lean as no mesh refinement near the air gap is needed or to strong mesh growth rates are forced [3].

The second approach is based on the method proposed by Arkkio. Instead of integrating over complex rotor or stator geometries the air gap is modeled as a separate domain and an integration over this domain is made using (4). B_{rad} is the radial and B_{tan} is the tangential component of the flux. The radii r_s and r_i enclose the air gap. The variable S is the surface of the enclosed area.

$$T_{Arkkio} = \frac{l}{\mu_0 (r_s - r_i)} \int_S r B_{rad} B_{tan} \, ds \qquad (4)$$
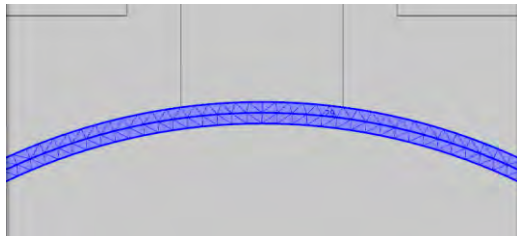

Figure 10 Integration domain (Arkkio method)

This method leads to very good results as the calculated torque is robust against the type of meshing elements and number of elements in the air gap. In Fig. 11 both methods using the stress tensor are compared using triangular and rectangular elements in the air gap.
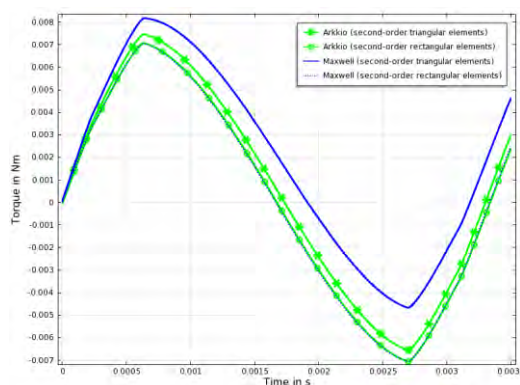

Figure 11 Benchmarking cogging torque calculations

The reason for the insensibility of the method proposed by Arkkio is the integration over a surface instead of a contour. This reduces the wrong representation of the magnetic vector potential due to one layer of triangular mesh elements directly at the rotor or stator contour.

Another aspect of the meshing process is the number of elements in tangential direction of the air gap. When interpreting the flux in the air gap as a sum of sinusoidal waves it is crucial to keep the number of elements in a reasonable relation to the highest order wave to be observed correctly. The most common value is ten elements per wavelength.

Parts of the model without big radii are meshed with rectangular elements as a better relation between number of elements and area can be reached. Very complicated geometries of the model with sharp corners or small radii are meshed with triangular elements. As the user does not see the mesh under automated conditions the scripting of the automated meshing process is very demanding. The meshing size and type must be adapted to the geometry but also to the researched property.

All this mentioned aspects are used to derive rules for the meshing process in EaSync leading to an adapted mesh which satisfies the geometrical and physical needs for a stable and accurate modeling.

4. The measuring rig

The measuring is based on the DUT (device under test), a torque flange, a dc motor with gear (1:111) and a hysteresis brake.

Figure 12 Measuring rig

These elements are connected through clutches to reduce torque spikes. The dc motor is able to rotate the system with less than one revolution per minute and with more than 100 revolutions per minute.

The slow turning is needed to measure torques without influence effects due to dynamics. The fast turning is needed for a startup of the hysteresis brake. The dc motor is controlled by a speed regulator using the encoder. The original motor speed is measured without gear ratio. This makes a good speed regulation despite slow turning possible.

The torque flange measures up to 1 Nm in both directions and is overloadable up to 2 Nm. The accuracy is high enough the measure

differences of 1mNm. The measurement principle is based on strain gauges and a contactless transmission using optocouplers. The flange includes an encoder with 360 pulses per revolution which leads to an accuracy of 0,25° when using quadruple evaluation.

The hysteresis brake is shown in Fig. 13. The rotation of the rotor through the magnetic field of the slotted stator forces a constant reversal of magnetism. A reversal of magnetism leads to power loss because of the magnetic hysteresis of the rotor material. This effect generates a torque against the rotation of the rotor which is proportional to the applied current. The brake generates up to 0.65 Nm applying 0,3 A. The generated offset improves the measuring of the cogging torque because of the nonlinearity around 0 Nm caused by the torque sensing flange.

5. Educational Aspects

The EaSync project involves all kind of engineering students at the Ostfalia University. Constructional projects like the first version of the measuring rig were designed by students in project works during the fourth Bachelor semester. An evaluation interface built in LABVIEW® was designed by Master students to apply Fast Fourier Transformations to the measured torques. The design and assembly of a measuring rig for permanent magnets is part of a single student research project. This measuring rig allows the analysis of rotors and their magnetization along their surface using a flux measuring device. Finally the presented measuring rig and EaSync itself is part of a master thesis and a dissertation project.

6. Conclusion

With the described methods EaSync covers the basic tools to design a synchronous machine and proof existing concepts. By choosing the adequate meshing and torque calculation method automatically imprecise calculations can be avoided. Add the current state the machine library is very limited as only one type of machine with simple geometry is included. The ongoing Master thesis and dissertation project will expand this library and add designing processes to EaSync. This will allow the design of various machine types from the scratch combing analytic and FEA models in one workbench.

7. References

[1] João Pedro A. Bastos and Nelson Sadowski. *Electromagnetic Modeling by Finite Element Methods*. Addison Wesley, Marcel Dekker, 2003.

[2] F. Jurisch. *Cogging in electrical machines: A new overview and measures to influence the cogging torque*. SPS/IPC/Drives Session Motoren, pp 613-620, October 2003.

[3] Germar Müller, Karl Vogt and Bernd Ponick. *Berechnung elektrischer Maschinen*. Wiley-VCH, 2008.

[4] Christoph Schlensok and Dirk van Riesen. *Cogging-Torque Analysis on Permament-Magnet Machines by Simulation and Measurement*. Technisches Messen 74 (2007) 7-8, June 2007.