Multi-Physics Simulation of a Synchronous Claw-Pole Alternator for Automotive Applications

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Abstract

Non electromagnetic design criteria for electrical machines, such as the limitation of the overall size, maximum temperature or efforts to extend the service life are of growing importance in automotive applications. In order to avoid expensive prototyping, powerful simulation tools are needed to analyze the machine behavior from the earliest design stage. Key aspect for multi-physics simulation, capable of addressing electromagnetic as well as thermal and mechanical aspects of the problem at a time, is the data exchange between subsystems of different natures, as well as the I/O operations with external data.

This paper describes a multi-physics simulation of a synchronous claw-pole alternator with focus on the interaction between electrical and thermal parts. The different levels of refinement of the model, the model decision and simplifying assumptions that have been done are also discussed in this paper.

I. INTRODUCTION

Separate simulations for the electromagnetic, mechanic and thermal design mean state of the art for the simulative part of the design process of electrical machines. Improved computing power allows for more complex simulations, combining different natures and exchanging parameter interactively at runtime. Due to the complex environment of multi-physics simulations, both modeling approach and model refinement, need to be evaluated carefully.

II. SIMULATION PROPERTIES

A. Simulation Tool

Simplorer [1] is used for all simulations considered in this paper. The opportunity of simulating electromagnetic, thermal, mechanic and problems is provided.

Simplorer also allows for various modeling approaches. Models composed from standard signal blocks, implemented in C or C++, as well as macros in VHDL-AMS, can be processed.

B. Component Modeling

The proposed modeling consists in selecting the most efficient approach for each subsystem. The electrical subsystem, representing the electromagnetic description of the machine is implemented in VHDL-AMS (Very High Speed Integrated Circuit Hardware Description Language for Analog and Mixed Signals) [2].

The mechanical subsystem is included in the set of differential equations describing the electromagnetic machine behavior. Mechanical parameters characterizing the operational point, such as the speed and the torque applied to the (crank) shaft, are provided externally. The resulting speed-torque feedback of the alternator is considered in the electromagnetic machine model. All peripheral aspects, such as semiconductors for the rectifier, auxiliary vehicle power system components, meters (voltage, ampere, heat, temperature) are taken as block models from standard libraries. Their implementation is not of interest here.

Due to common modeling, the thermal machine model usually appears as heat-source plot composed of discrete standard components. An alternative implementation in VHDL-AMS is therefore not found most obvious modeling opportunity due to the distinctive complex network structure of the heat source plot. Anyway, an analogous VHDL-AMS implementation may have advantages concerning time expenditure for model synthesis and modification and the duration of the simulation time as well. The comparison of both modeling opportunities for the thermal component and furthermore evaluation of the most reasonable choice is also subject of this paper.

III. SIMULATION

The simulation sheet consists of two sub models; thermal and electromagnetic (the latter containing mechanical features) placed on the same sheet level and with equal priority. The parameter exchange is performed runtime-dynamically at each time step. The simulation time step applies for both sub models. Reasonable values for the minimum and maximum time step need to turn out in test simulations, satisfying precision requirements and a short total computing time. By neglecting the dynamic parameter exchange between the sub systems, utilizing static parameters instead, both thermal and electromagnetic simulations run independently on different sheets.

A. Electromagnetic Model

The electromagnetic model is implemented in VHDL-AMS. This approach turned out to be the most efficient from the point of view of computing time, general handling, extensibility and modifications.

The implemented equations describing the electromagnetic and mechanical machine behavior may appear under differential or integral form without result discrepancies. There is no adaptation to any particular algorithm required for VHDL-AMS model usage. The write out of (1)-(14) is sufficient.

Due to the distinctive 3D shape of the claw-pole rotor, the mutual inductance between rotor and stator need to be projected into a 2D plane for a spatio-temporal simulation. This allows for a treatment as regular salient-pole synchronous machine. The formal description of the mutual inductance between rotor and stator (9)-(11) is basically composed of a constant factor L_d and oscillations of harmonics accounting for the claw shape, representing the air gap.

Flux-linkage equations

$$i_U = \frac{\psi_U}{L_U} - \frac{L_{UV}}{L_U} i_V - \frac{L_{UW}}{L_U} i_W - \frac{L_{UF}}{L_U} i_F \tag{1}$$

$$i_V = \frac{\psi_V}{L_V} - \frac{L_{UV}}{L_V} i_U - \frac{L_{VW}}{L_V} i_W - \frac{L_{VF}}{L_V} i_F \tag{2}$$

$$i_W = \frac{\psi_W}{L_W} - \frac{L_{UW}}{L_W} i_U - \frac{L_{VW}}{L_W} i_V - \frac{L_{WF}}{L_W} i_F \tag{3}$$

$$i_F = \frac{\psi_F}{L_F} - \frac{L_{UF}}{L_F} i_U - \frac{L_{VF}}{L_F} i_V - \frac{L_{WF}}{L_F} i_W \tag{4}$$

Voltage equations

$$\psi_U = \int \left(u_U - i_U R_U \right) dt \tag{5}$$

$$\psi_V = \int \left(u_V - i_V R_V \right) dt \tag{6}$$

$$\psi_W = \int \left(u_W - i_W R_W \right) dt \tag{7}$$

$$\psi_F = \int \left(u_F - i_F R_F \right) dt \tag{8}$$

Mutual-inductance equations

$$L_{UF} = L_d \cdot \cos(\gamma) \tag{9}$$

$$L_{VF} = L_d \cdot \cos\left(\gamma - \frac{2\pi}{3} \right) \tag{10}$$

$$L_{WF} = L_d \cdot \cos\left(\gamma - \frac{4\pi}{3} \right) \tag{11}$$

Motion equations

$$\begin{aligned} M_{el} &= \frac{p}{\omega} \cdot \dot{L}_{UV} \cdot i_U \cdot i_V + \dot{L}_{UW} \cdot i_U \cdot i_W + .. \\ &... + \dot{L}_{VW} \cdot i_V \cdot i_W + \dot{L}_{UF} \cdot i_U \cdot i_F + ... \\ &... + \dot{L}_{VF} \cdot i_V \cdot i_F + \dot{L}_{WF} \cdot i_W \cdot i_F \end{aligned} \tag{12}$$

$$\gamma = \gamma_0 + \int \omega \; dt \tag{13}$$

$$\dot{\omega} = \frac{p}{J} \cdot \left(M_{el} - M_{Load} \right) \tag{14}$$

For the sake of simplicity, (9)-(11), the harmonics are not shown besides the fundamental. The factor L_d previously assumed constant, is de facto a symbolic representative for a saturation and speed dependent constant variable, read by the simulator from external data files at runtime. The corresponding look-up table is pre-determined by means of Finite Element (FE) simulations.

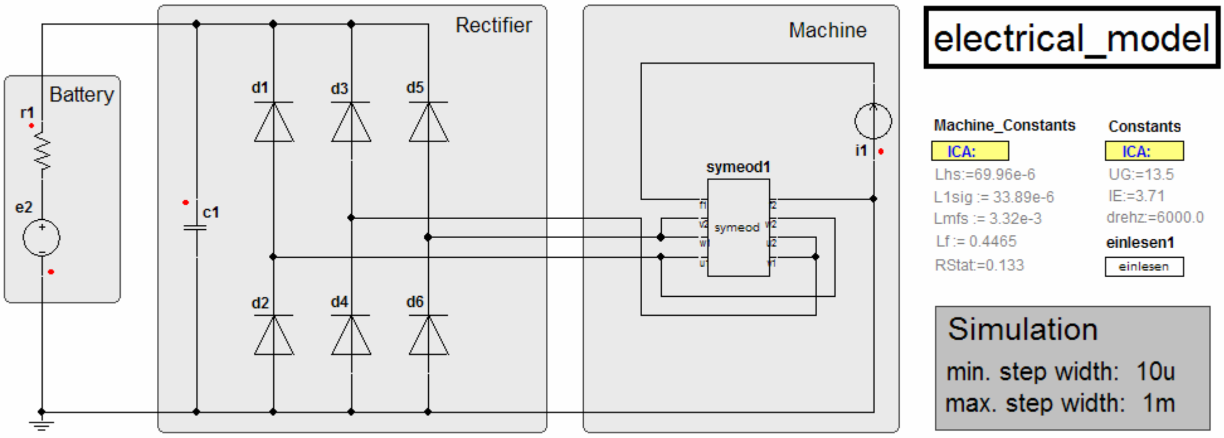

Fig. 1: Schematic of the electromagnetic part of the simulation.

The claw-pole alternator model is embedded into a simplified vehicle power-supply system, as depicted in Fig. 1 [3]. Only the electrical components need to be modeled. Mechanical parameters such as torque and speed are provided by external data files. This does not require particular modeling of the crank shaft. Torque-speed feedback is considered in (14).

Speed and saturation dependent inductances are stored in look-up tables. Smart input routines read and process the corresponding parameters during the simulation.

The temperature dependency of the resistances (causing ohmic losses) is implemented as a bi-directional parameter exchange between electrical and thermal simulation subsystem. The temperature affects the ohmic resistance of stator and rotor winding, as expressed by (15).

$$R = R_{20} \cdot \left(1 + \alpha_{Cu} \cdot \Delta \vartheta\right) \qquad (15)$$

$$\mathrm{R}_{20} = \mathrm{R}\ (\vartheta = 293\mathrm{K}),\ \alpha_{Cu} = \text{temp. const.}$$

A variation of the applicable winding resistances affects the currents, which in turn have an effect on the ohmic losses, to loop back to the thermal model.

B. *Thermal Model*

The heat-source plot of Fig. 2 represents the thermal model of an air-cooled claw-pole alternator [4] graphically composed of standard blocks. Peripheral blocks such as input blocks to define the operational state (speed, etc.) are not displayed here for clarity purposes. Resistors either stand for the thermal resistance of solid material or for the transfer-resistance between machine parts. Thermal resistance and thermal capacitance are computed directly from geometry information and material parameters, which allows for a convenient parameter variation.

Heat sources represent losses to appear in lumped elements. Ohmic losses in stator and rotor are provided by the electrical model. Iron and friction losses are stored in external look-up tables, and requested by the simulator at runtime. The corresponding load case is determined by the electromagnetic model.

Storage of the induction for a series of operational states, dependent on excitation and frequency, and the Steinmetz equation for the determination of iron losses are also conceivable.

The implementation using function blocks as of figure 2 leads so extended simulation times for multi-physics simulations exchanging parameters values with the electromagnetic model due to the exchange of parameters over different simulation sheet levels.

An analogous implementation in VHDL-AMS is used for comparison reasons. It basically shows comparable model structure as the described electrical model. Textual equations as well as port maps are utilized instead of graphical picking of standard blocks.

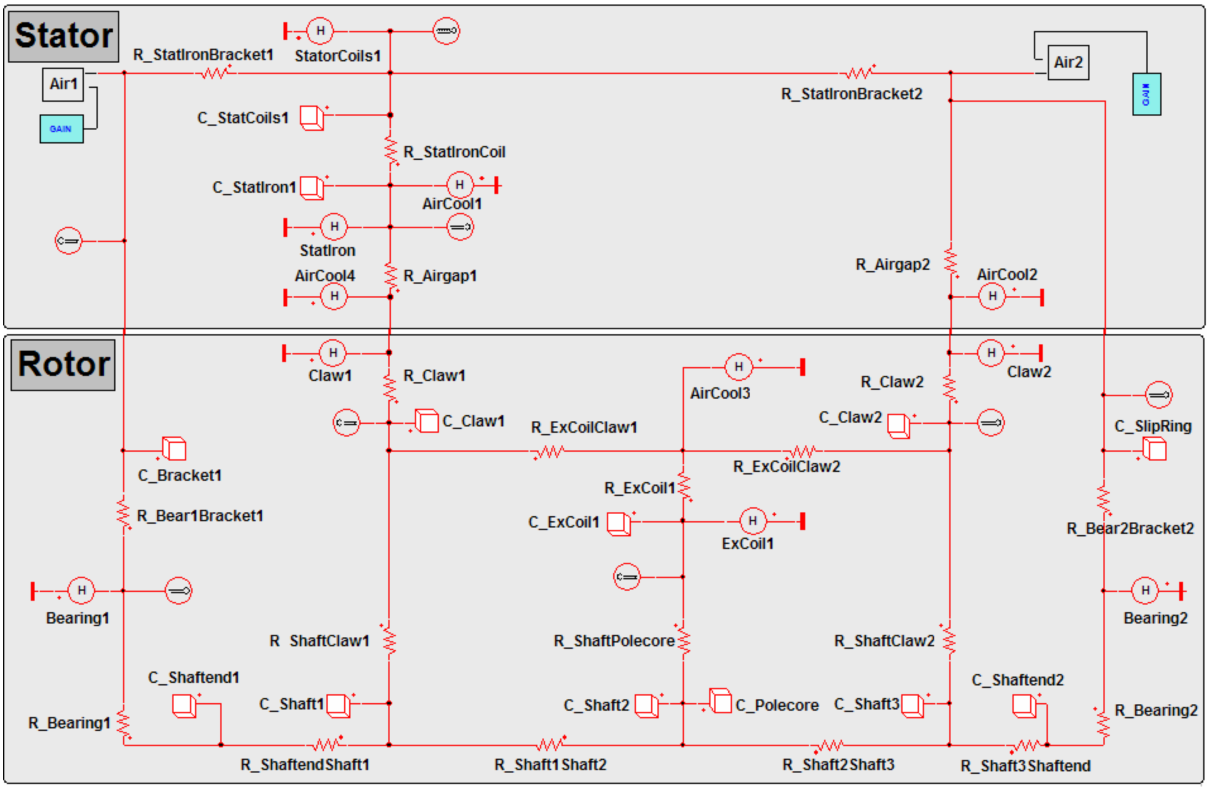

Fig. 2: Heat-source plot of the claw-pole alternator (air cooled).

In this case the entire thermal model consists of not more than 90 source code lines, subjectively felt more clear than the wide spreading graphical solution, ranging over a couple of letter pages when printed.

The genuine simulation solely using VHDL-AMS for both electromagnetical and thermal model leads to a decreased computing time compared to the formerly described mixed modeling variant.

Since both electromagnetical as well as thermal machine components are now implemented in VHDL-AMS, the opportunity of combining into one single model is provided. This eases initialization and linking of exchange parameters between both natures (such as losses or temperature) since the exchange parameters are already internally linked for combined models at the time of implementation. Therefore the general handling is improved. A significant reduction of the computing time can not be recognized for combined models compared to genuine models as of above.

IV. RESULTS

The simulation results match very well to measurements taken as a reference – this applies for both VHDL-AMS combined with block modeled simulation as well as for solely VHDL-AMS modeled simulations.

Discrepancies between simulation and measurements result from the geometrical simplification of the claw-shaped rotor. Neglecting the claw chamfers on the leading and leaving edge causes errors up to 8%.

Thermal simulation errors are due to the inaccurate determination of heat generated by friction losses or the iron and eddy current losses, e.g. in the stator laminations.

Negligible absolute errors between thermal simulations results of both VHDL-AMS and block modeling are detected when comparing. Figure 3 shows the absolute error of the simulation results using VHDL-AMS implemented on the one hand and the block assembled thermal machine model on the other hand.

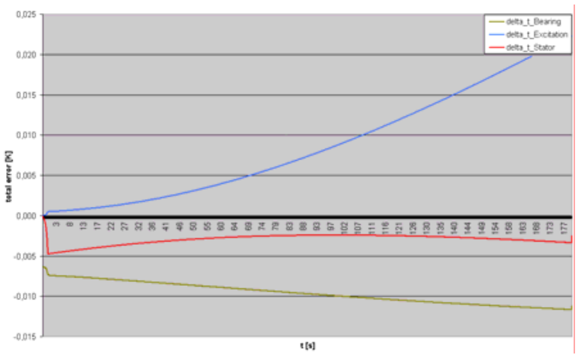

Fig. 3: Total error of simulation results between both modeling opportunities.

Selected temperatures (stator windings, exciter windings, bearings) are depicted in Fig. 3.

Usually coupled thermal and electrical simulations use behavioral models for the electrical simulation instead of detailed electrical models as utilized here. Since each separate simulation (electrical, thermal) only takes about 15 seconds total computing time with reasonable time steps (min. 10 μs, max. 1 ms) for a 10 second period (Pentium 4m, 1.8 GHz) when simulated independently, a combined simulation with usage of components with described models refinement appears reasonable.

The multi-physics simulation with bi-directional parameter coupling between thermal and electrical machine model increases the computing time significantly. A variation of the time step accelerates the simulation process of the given period on the one hand, but causes inaccuracies on the other hand.

The current waveform (and peak and average value) is badly represented (Fig. 4a, 4b) when time steps are too large.

Due to long time constants, the temperature plot is not affected, fast acting or transient phenomena as applicable for electromagnetic simulations do not apply for thermal simulations.

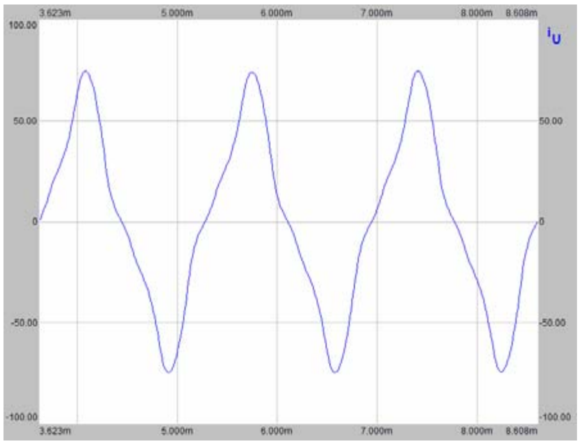

Fig. 4a: Current shape at 10 μs/1ms.

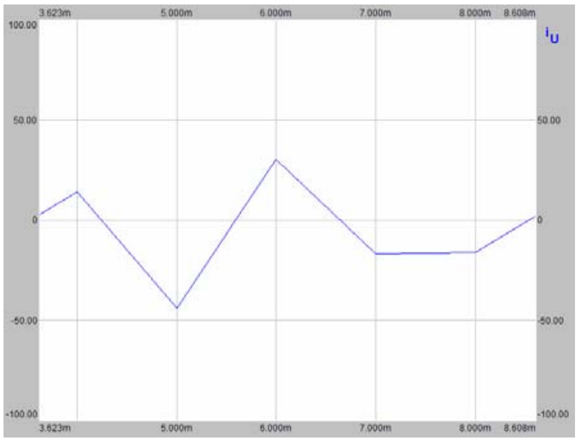

Fig. 4b: Current shape at 1000 μs/100ms.

When replacing the detailed electrical machine model by a three phase current source, driving a sinusoidal current of equivalent value (Fig. 4), with stator and rotor winding inductance and resistance, the computation time is still high. The difference between the idealized sinusoidal shape of the current sources and that of the real model are acceptable for simulations with focus on the thermal behavior.

Influences of transient electromagnetic phenomena on the thermal behavior can not be considered using the current source simplification (Fig. 5); torque-speed feedback can not be considered as well.

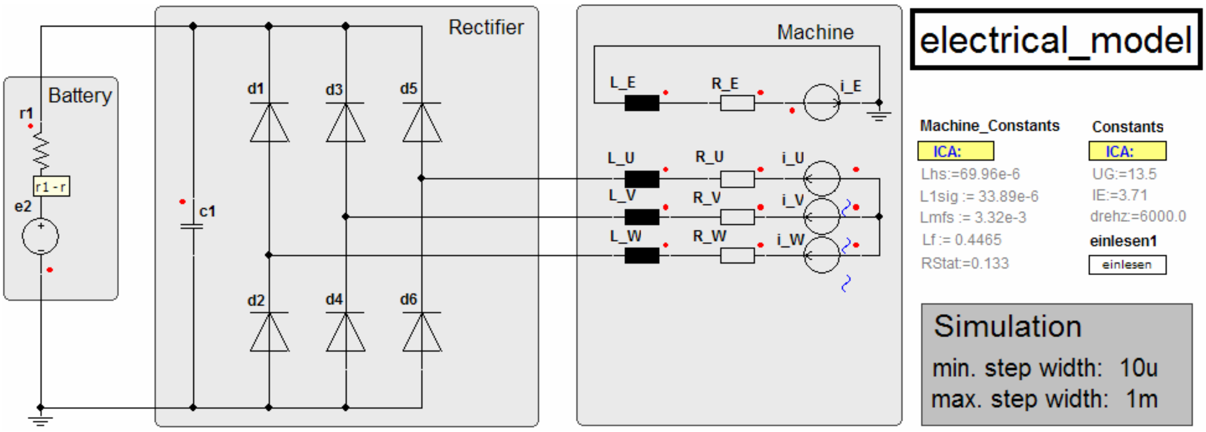

Fig. 5: Electrical subsystem, machine replaced by a three-phase current source.

V. CONCLUSION

The variation of the model refinement from highly detailed to roughly simplified models does not lead to a significant reduction of the computing time for this application. This leads to the conclusion, that the model refinement level is almost independent from the computing time in simulations of high complexity, such as multi-physics simulations. Due to the complexity of the thermal simulation, a down-stripped heat-source plot with feasible simplifications needs to be tested under equivalent circumstances. These results need to be verified on different simulation tools with focus on the computing time discrepancies between sole thermal and electromagnetic and a multi-physics simulation as well.

REFERENCES

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