COMBINED ANALYTICAL AND NUMERICAL COMPUTATION APPROACH FOR DESIGN AND OPTIMIZATION OF 6-PHASE CLAW-POLE ALTERNATORS

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ABSTRACT

Automotive applications are mostly designed to low costs. Efforts to reduce noise, increase efficiency and expand duty cycles call for optimized machine designs. Sophisticated machine designs require long FEA computing times for the optimization process. Combinations of calculation approaches decrease the total computing time and therefore costs significantly. This paper shows a combined analytical and numerical calculation approach, using analytical means for pre-design to match power requirements (torque, speed, current) and FE calculation for magnetic verification. The method is applied on a 6-phase claw-pole alternator design.

INTRODUCTION

The design of common 3-phase claw-pole alternators basically consists of the DC excited rotor with characteristic claw fingers and the stator, equipped with a 2-layer 3-phase winding. The expansion of the winding system up to 6-phases reduces DC-link current ripples of the rectifier and therefore expands the duty cycle of the rectifier components. Besides current ripple reduction, utilization of 6-phases reduces demands on ampacity of components of each phase.
The 6-phase winding is composed of two independent parallel 3-phase windings (Fig. 1, 2).

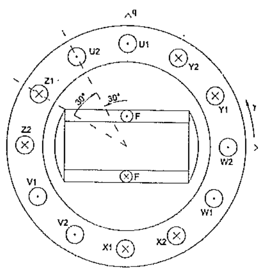

Fig. 1: 6-phase synchr. machine

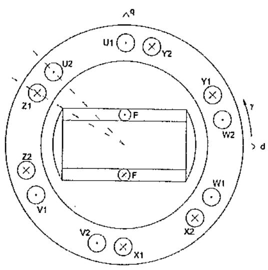

Fig. 2: varied stator arrangement

The obvious arrangement of stator phases (Fig. 1) does not neccesarily need to mean best possible solution due to electric and magnetc requirements. The determination of appropriate winding configurations (example Fig. 2) is subject to computational analysis.

APPROACH

Both 3-phase windings may be displaced of n-times the slot pitch of the stator teeth (example given Fig. 2). Variation calculations determine the most effective winding arrangement.

Analytical Part

In a first step of the combined computation method current peak values as well as *rms* values vs. displacement angles of the two independent 3-phase winding systems are analyzed analytically.
At this early stage of design, phase currents of the alternator are assumed as being of sinusoidal shape for simplification reasons. This approximation is reasonable for both considered speed and excitation ranges entirely. The implementation in Matlab (1) is brief. Phase current equations for winding systems #1 and #2 are based on (1), (2):

$$i_{1\ k+1} = \hat{I} \cdot \sin\left(\omega t + \frac{2 \cdot k \cdot \pi}{3}\right) \qquad (1)$$

$$i_{2\ k+1} = \hat{I} \cdot \sin\left(\omega t + \gamma + \frac{2 \cdot k \cdot \pi}{3}\right) \qquad (2)$$

displacement angle γ, k=0, 1, 2

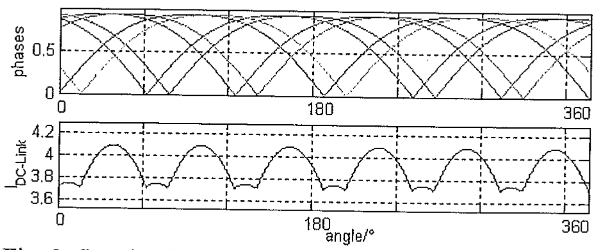

Fig. 3: $I_{1,2k}$ (top), $I_{\text{DC-link}}$ (bottom), 45° displaced

The accordant DC-link current ensues to:

$$i_{DC-Link} = \sum_{k=0}^{5} \left| i_{12,k+1}(t) \right| \qquad (3)$$

Due to counteracting inductive influences of the phase currents, peak values of both phase current and DC-link current vary with γ.

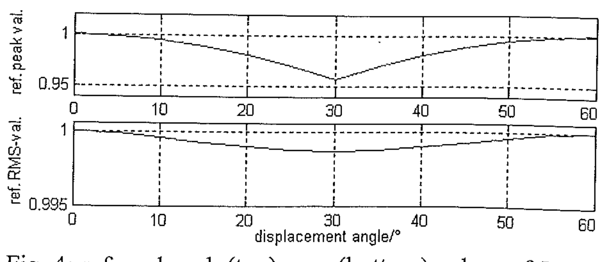

Fig. 4: referred peak (top), rms (bottom) values of $I_{1,2k}$

Figure 4 shows referred (on max. occuring value) peak and rms values of the DC-link current in the symmetry cutout $0° \le \gamma \le 60°$.
As per analytical calculation, the peak value decreases down to 95% of the maximum occuring value, whereas

the rms value does not fall off significantly at various displacement angles γ.

Mutual inductive influences of stator phase currents, varying with displacement angle γ, have an effect on the shape of the phase currents, affecting magnitude and frequency. Harmonic analysis therefore requires authentic description of current waveforms, taking particular winding arrangements into account.

Current waveforms, now regarding inductive influences of all phases of the system can be determined analytically, also taking the accordant displacement angle between the two winding systems into account.

$$i_{11} = \frac{\psi_{11}}{L_{11}} - i_{21}\frac{L_{11\_21}}{L_{11}} - i_{31}\frac{L_{11\_31}}{L_{11}} - i_{12}\frac{L_{11\_12}}{L_{11}} \ldots$$

$$\ldots - i_{22}\frac{L_{11\_22}}{L_{11}} - i_{32}\frac{L_{11\_32}}{L_{11}} - i_{\mathrm{F}}\frac{L_{11\_\mathrm{F}}}{L_{11}} \qquad (4)$$

Equation (4) expresses the phase current 1 (=U) of system #1, with accordant winding system displacement mainly regarded in the inductive coupling of phase currents 1 (=U), 2 (=V), 3 (=W) of system #2.

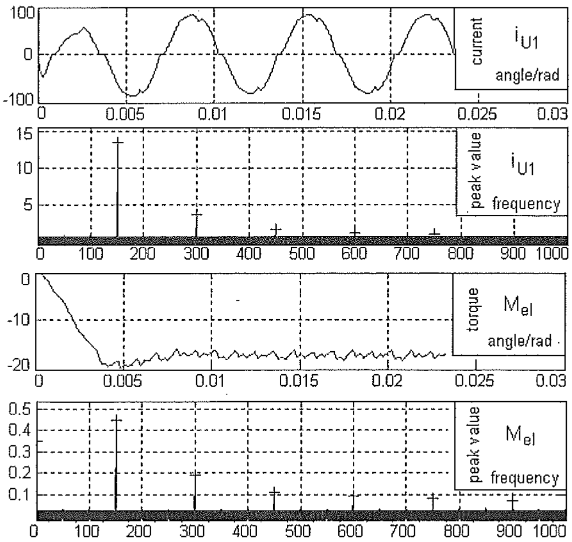

Fig. 5: current i_{11} waveform (top) / FFT (2nd), torque M FFT (3rd)characteristic (bottom)

As a result, deriving from the analytical pre-designing process, electrical requirements, such as e.g. current limitations, torque and speed demands are matched. This leads to a selection of reasonable winding configurations out of any possible arrangement.

Numerical Part

The resulting configuration of the electrical pre-designing process does not neccesarily need to state a reasonable choice from the magnetic point of view.

For the given machine type, featuring variable stator winding arrangements, an accordant parasitic flux distribution may occur, leading to asymmetric saturation in stator teeth and yoke, which may ensue to unwanted and parasitic effects.

Therefore numerical methods, such as FE calculations, are to be utilized to doublecheck both on proper magnetic design as well as on correct results of the analytical calculations of electrical and mechanical values (current, torque, speed, etc.).

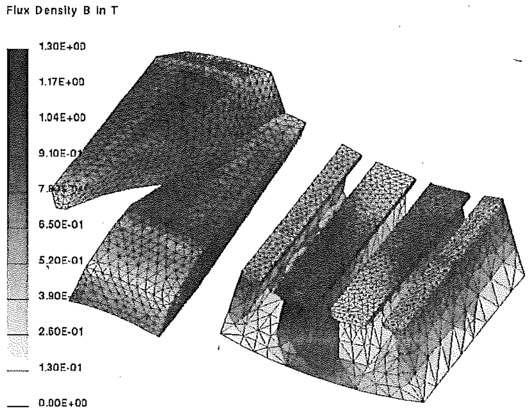

Fig. 6: flux density distribution (FE calculation results)

As an additional feature to the opportunity of described proper magnetic design verification, FE calculations allow for further analysis, such as exerted forces on the machine body, structure dynamics and noise.

The given example of a 6-phase claw-pole alternator is magnetically designed using our object-oriented solver environment iMOOSE (2) with static and transient 3D solvers.

RESULT

Torque and current results, deriving from the analytical pre-design process match very well with FE calculation results. A selection of arrangements of the two independent stator winding systems turned out to be favorable during the analytical pre-design.

As a major benefit of the combined analytical and numerical approach, the number of FE calculations are reduced, since appropriate machine configurations are already pre-selected in time saving analytical calculations.

CONCLUSION

The method of analytical pre-determination of appropriate electrical machine design, in combination with numerical methods for the magnetic design is presented in this paper.

This method provides a time saving alternative to solely FE calculation for both electrical and magnetic design and optimization of electrical machines.

Besides acceleration of computation, the combination of analytical and numerical methods allows for cross-verification of results of the electrical design.

1. Matlab/Simulink, homepage: www.mathworks.com
2. iMOOSE – innovative Modern Object-Oriented Solver Environment (partly open source), homepage: www.imoose.de
3. Ansys Inc., homepage: www.ansys.com