Current-Waveform Analysis of 6-phase Claw-Pole Alternators using VHDL-AMS Implementation in Simplorer

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I. ABSTRACT

Automotive applications are mostly designed to low costs. This applies for both development and manufacturing. Reducing noise, increasing efficiency and expanding duty cycles of electrical machines become of increasing importance and therefore call for optimized machine designs. The optimization process is not necessarily bound to approved machine designs. In order to avoid expensive prototyping, authentic simulation models are required for analysis purposes.

This paper deals with the current-waveform analysis of a 6-phase claw-pole alternator with arbitrary stator winding arrangements. Here, the machine is modeled in VHDL-AMS to be simulated with Simplorer. VHDL-AMS states a standardized hardware description language (IEEE 1076.1) for analog and mixed signals, mostly used for integrated circuits. It is also a proven means for the modeling and analysis of electrical machines.

II. INTRODUCTION

The considered claw-pole alternator is solely operated in generator mode for various speed and load cases. The simulation environment is characterized by a 6-phase uncontrolled rectifier bridge, consisting of two 3-phase bridges connected in parallel. A battery is connected to the DC-link to be powered by the generator (Fig. 1).

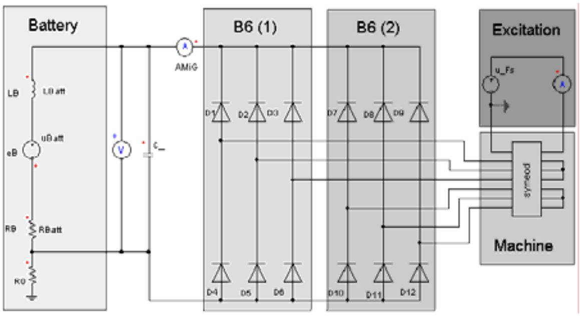
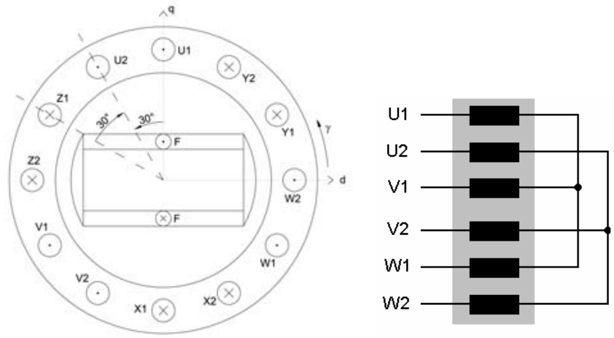


Fig. 1: Simulation Environment (Machine, B12 Bridge, Battery).

The design of common 3-phase claw-pole alternators basically consists of a dc excited rotor with characteristic claw fingers and the stator, equipped with a 3-phase winding. The equation set for claw-pole machines is based on that of a salient-pole synchronous machine. The particular claw shape of the rotor is regarding harmonics. The expansion of the winding system up to 6-phases e.g. reduces dc-link current ripples of the rectifier and therefore expands the duty cycle of rectifier components. Besides the current ripple reduction, the utilization of 6-phases reduces the demands on the ampacity of components of each phase.

III. MACHINE STRUCTURE

The 6-phase winding of the machine considered here is composed of two independent parallel 3-phase windings (Fig. 2a).



(a) basic stator arrangement. (b) winding arrangement.
Fig. 2: 6-Phase Salient-Pole Synchronous Machine (SM).

The stator consists of 72 slots, resulting in a slot pitch of $\gamma = 5°$ of the stator teeth. Both independent 3-phase windings are displaced n-times the slot pitch against each other. The arrangement of stator phases (Fig. 2a) using a winding displacement of $\gamma = 30°$ is subject to the studies presented in this paper.

The differential system of equation describing the machine structure based on the electromagnetic behavior basically consists of seven current and seven flux linkage equations each, six equations regarding the position dependent mutual inductances between rotor and stator and one motion equation. Solely the current equations are subject to studies of this paper. The accordant equation for phase U1, which is exemplarily chosen here, reads:

$$i_{\mathrm{U1}} = \frac{\psi_{\mathrm{U1}}}{L_{\mathrm{U1}}} - i_{\mathrm{V1}} \cdot \frac{L_{\mathrm{U1V1}}}{L_{\mathrm{U1}}} - i_{\mathrm{W1}} \cdot \frac{L_{\mathrm{U1W1}}}{L_{\mathrm{U1}}} - i_{\mathrm{U2}} \cdot \frac{L_{\mathrm{U1U2}}}{L_{\mathrm{U1}}} \ldots$$
$$\ldots - i_{\mathrm{V2}} \cdot \frac{L_{\mathrm{U1V2}}}{L_{\mathrm{U1}}} - i_{\mathrm{W2}} \cdot \frac{L_{\mathrm{U1W2}}}{L_{\mathrm{U1}}} - i_{\mathrm{F}} \cdot \frac{L_{\mathrm{U1F}}}{L_{\mathrm{U1}}} \qquad (1)$$

IV. VHDL-AMS MODELING AND SIMULATION

VHDL-AMS models contain definitions of required variable parameters, ports and constants as well as the accordant differential system of equations. The latter are supposed to contain current, flux-linkage, mutual inductance, and motion equations (e.g. as of eqt. (1) - (7)).

The implementation of VHDL-AMS model files can be performed in any editor, being then available for the import as macro in the simulator environment, such as

Simplorer, and ready for use. The VHDL-AMS syntax is found plausible in general. Differential equations are easy to read and appear in their edited form:

i_U1 == (psi_U1/L_U1)-(i_V1*(L_U1V1/L_U1))-..
...-(i_W1*(L_U1W1/L_U1))-(i_U2*(L_U1U2/L_U1))-...
...-(i_V2*(L_U1V2/L_U1))-(i_W2*(L_U1W2/L_U1))-...
...-(i_F*(L_U1F/L_U1)); (1')

The utilization of VHDL-AMS macros in Simplorer provides the opportunity to arbitrarily declare any variable as output variable. This allows for a purposive analysis of variables in the simulation.

V. CURRENT-WAVEFORM ANALYSIS

Due to the provided opportunity of declaring any variable, addend or part of a differential equation as output variable, current waveforms can be analyzed component wise.
This feature becomes of increasing significance with growing complexity, if particular influences due to flux linkage do not appear apparently.
For the considered case of the 6-phase claw-pole alternator, the current trace is characteristic for the group of synchronous machines as a matter of principle, but shows some peculiarities due to the special design, taking the implementation of 6 stator phases into account (Fig. 3).

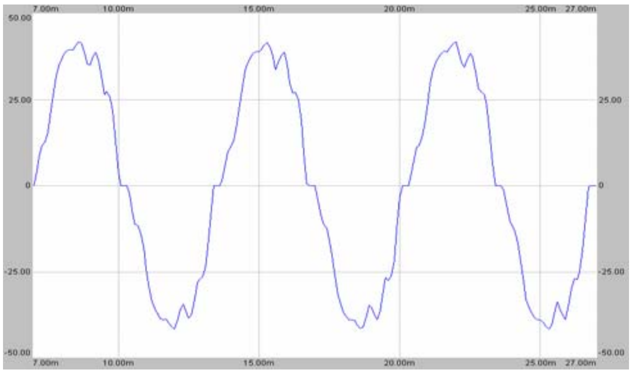


Fig. 3: Current waveform i_{U1} of a 6-phase claw-pole alternator.

The current characteristic of i_{U1}, shown in Fig. 3 complies with equation (1'). The influences of respective addends of equation (1') are analyzed stepwise by defining single equation elements as output variables.
Fig. 4 shows the particular characteristic of the self-induction current-component caused by the respective flux-linkage in phase U1 (1'1) as well as the current component derived from the excitation in the rotor windings (1'2).

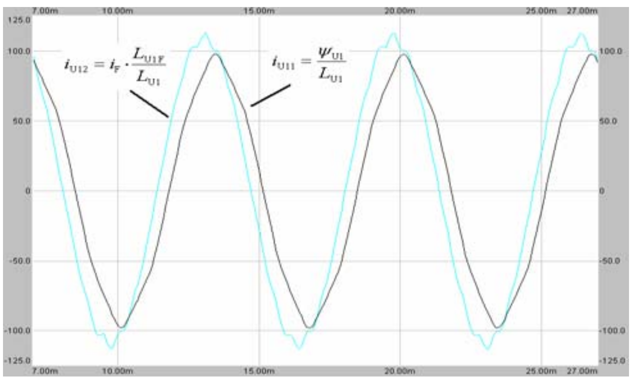


Fig. T: traces due to equations (1'1) and (1'2).

i_U11 = (psi_U1/L_U1); (1'1)
i_U12 == (i_F*(L_U1F/L_U1)); (1'2)

The addends of (1'1) and (1'2) are defined as output variables and are shown in Fig. 4, whereas the difference of both components (1'3) is plotted in Fig. 5.

i_U13 == (psi_U1/L_U1)-(i_F*(L_U1F/L_U1)); (1'3)

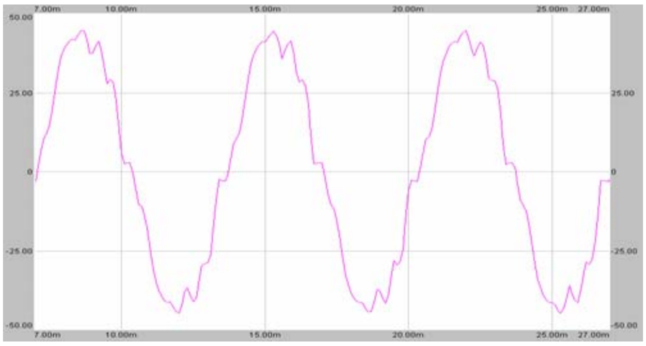


Fig. 5: Difference of equation (1'1) and (1'2).

The characteristic behavior shown in Fig. 5 matches to that of Fig. 3 very well. Except for the influence of the other stator phases causing a buckling of the trace.
It turns out, that the mutual induction current component of the excitation into the stator circuit of phase U1 causes dents in both upper and lower half wave of the current i_{U1}.
This dents derive from the influence of the rotor magnet wheel, due to its claw-pole shape.
The variation of simulation properties leads to the conclusion that the shape and the intensity of the described bents are dependent on the excitation and the load case of the machine.

VI. CONCLUSION

The current characteristics of the described 6-phase claw-pole alternator are composed of the components of the mutual induction of all appearing current components. The accordant trace is of characteristic shape, whose detailed analysis requires a separation into the single applicable components.
The implementation of the machine model in VHDL-AMS and simulation in Simplorer allows for step wise and separated investigation of single current components.
This method is useful for the analysis in both regular and faulty cases. Besides the described regular operational states, the influences on the current shape can be easily determined for fault scenarios, since any variable is directly accessible.
The general current characteristic analysis process is shown in this digest. Detailed investigations of all applicable current induction components on the considered stator current trace i_{U1} using the described method will be presented in the full paper.