Study of hybrid excited synchronous alternators for automotive applications using coupled FE and circuit simulations

Thomas Finken and Kay Hameyer
Institute of Electrical Machines, RWTH Aachen University
Schinkelstr.4, 52056 Aachen, Germany; Email: thomas.finken@iem.rwth-aachen.de

***Abstract*— In this paper an alternative arrangement to conventional Lundell automotive generators is examined. This geometry is characterized by hybrid excitation combining the high energy density of permanent magnets and the controllability of commonly used electrical excitation. A simulation of the alternator using the finite-element method (FEM) is accomplished to optimize the rotor geometry and to develop a design, ready for prototyping. The formulation for the transient solver is given and the coupling with an external circuit exemplified. The accomplished studies, simulations and geometry optimizations are presented. In a final step the simulations are compared to prototype measurements and confronted with conventional alternator geometries.**

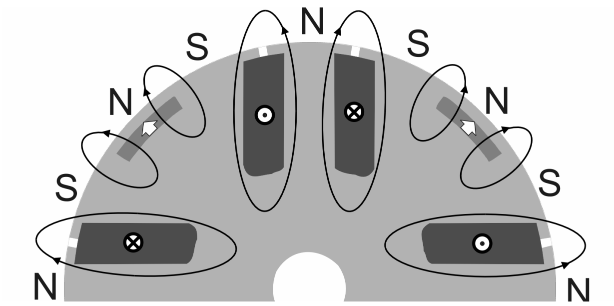

Fig. 1. Schematic geometry sector of examined rotor.

I. Introduction

The vehicle-power supply required for electrical equipment and charging of the battery contains an alternator. Due to an increasing power demand, alternators have to become more efficient. Thereby the increase of power is to be aimed at constant or less installation space and weight of the generator. Restricted improvement of existing alternator types leads to considerations on new and alternative designs.

An alternative machine design studied in present work consists of hybrid excited rotors, the magnetic excitation is generated by both permanent magnets and excitation windings. Electrical excitation gives the advantage of simple control of the magnetic field by the excitation current, but a more complicated construction and an increased copper expense. By development of new magnetic materials featuring higher energy densities, improved temperature stability and reasonable prices, the application of permanent excitation becomes more attractive and affords higher power densities. An important disadvantage of permanent excitation is the missing opportunity of field weakening, preventing appliance in automotive engineering previously. Gain of hybrid excitation is the combination of high energy density of permanent magnets and the controllability of electrical excitation [5].

II. Studied geometry

In the present work a 16-pole geometry is analyzed. It consists of four electrical and four permanent excited poles of equal polarization, which are arranged alternately and symmetrically. The poles of opposite polarization are not generated by own excitation but by the return flux of 'active' poles (Fig. 1). Used permanent magnets are rare-earth magnets.

The actual pole number, and thus the behavior of the machine, depends on the excitation of the electrical poles. If the electrical excitation generates poles with same polarization as the permanent magnets, a symmetric 16 poles field is shaped - induced voltage and absorbed power is highest. With no electrical excitation the field has 8 asymmetric poles. Due to the asymmetry, the flux crossing the stator coils is unequal zero, so induced voltage is unequal zero and power will be absorbed. If the excitation current is negative, the rotor field has 8 symmetric poles. Coil crossing flux will be zero, so voltage and absorbed power will also be zero.

III. The applied transient solver

To simulate the alternator in chosen operation points, confronts with the difficulty of unknown stator currents and their reaction on the entire magnetic field. Therefore the accomplished finite-element simulation requires a transient solving process which takes the geometry rotation into account and is coupled to an electric circuit. The applied in-house solver is part of an object-oriented solver package [1]. The transient FEM formulation takes the rotational movement into account by means of time-stepping, so two finite-element meshes have to be handled. The 2-D $\vec{A}$-approach, using the magnetic potential $\vec{A}$ in all regions, has to be solved in the complete model Ω. Its Galerkin formulation is [1]:

$$\int_\Omega \left(\text{grad}\,\alpha_i \cdot \nu\ \text{grad}\,A_z(t) + \alpha_i \cdot \frac{d}{dt}\sigma A_z(t)\right)d\Omega = \int_\Omega \left(\alpha_i \cdot J_z(t) + \text{rot}\,(\alpha_i \vec{e}_z)\cdot \nu \vec{B}_r\right)d\Omega. \quad (1)$$

The material parameters ν and σ represent the nonlinear reluctivity and the linear conductivity. The shape function of an element is defined by α_i. $J_z(t)$ describes the z-component of the given coil current-density while $B_r(t)$ defines remanence.

In the case of unknown stator currents the electromagnetic computation has to be coupled with an electrical circuit. The magnetic potential $\vec{A}$ is still an unknown quantity of the system of equations. Furthermore two kinds of electric conductors are differentiated: the solid conductor with possible eddy currents and the wound conductor where, due to its thin wires, no eddy currents are possible. The unknown quantities are voltages for the solid conductors and currents for the wound conductors. The magnetic potential **A**, the potential difference $\Delta\mathbf{V}$ of solid conductors and the circuit-mesh current $\mathbf{I}_m$ are the unknown vectors of the system of equations. The system matrix of this FE approach is formulated in following equation:

$$\left.\begin{bmatrix} \Theta\mathbf{S}+\frac{1}{\Delta t}\mathbf{G} & -\Theta\mathbf{C} & -\Theta\mathbf{C}'\mathbf{D}'^T \\ -\Theta\mathbf{C}^T & \Delta t\Theta^2\frac{1}{\mathbf{R}} & -\Delta t\Theta^2\mathbf{D}^T \\ -\Theta\mathbf{D}'\mathbf{C}'^T & -\Delta t\Theta^2\mathbf{D} & -\Theta\mathbf{L}_m-\Delta t\Theta^2\mathbf{R}'_m \end{bmatrix}\right|_{n+1} \cdot \begin{bmatrix} A_{n+1} \\ \Delta V_{n+1} \\ I_{m_{n+1}} \end{bmatrix} =$$

$$\left.\begin{bmatrix} -(1-\Theta)\mathbf{S}+\frac{1}{\Delta t}\mathbf{G} & (1-\Theta)\mathbf{C} & (1-\Theta)\mathbf{C}'\mathbf{D}'^T \\ -\Theta\mathbf{C}^T & -\Delta t\Theta(1-\Theta)\frac{1}{\mathbf{R}} & \Delta t\Theta(1-\Theta)\mathbf{D}^T \\ -\Theta\mathbf{D}'\mathbf{C}'^T & \Delta t\Theta(1-\Theta)\mathbf{D} & -\Theta\mathbf{L}_m-\Delta t\Theta(1-\Theta)\mathbf{R}'_m \end{bmatrix}\right|_{n} \cdot$$

$$\begin{bmatrix} A_n \\ \Delta V_n \\ I_{m_n} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\Delta t\Theta^2 U_{m_{n+1}} - \Delta t\Theta(1-\Theta)U_{m_n} \end{bmatrix} \qquad (2)$$

Whereas the element matrices $\mathbf{G}$,$\mathbf{C}$ and $\mathbf{R}_k$ describe the regions of solid conductors and $\mathbf{G}'$,$\mathbf{C}'$ and $\mathbf{R}'_k$ describe regions of wound conductors. In case of coupled circuit simulation and considered rotational movement the element matrix **S** is:

$$S_{ij}|_{n+1} = l\int_F \mathrm{grad}\,\alpha_{i_{n+1}} \cdot \nu_{n+1}\mathrm{grad}\,\alpha_{j_{n+1}}dF \qquad (3)$$

$$S_{ij}|_{n} = l\int_F \mathrm{grad}\,\alpha_{i_{n}} \cdot \nu_{n}\mathrm{grad}\,\alpha_{j_{n}}dF \qquad (4)$$

IV. Results and Accomplished Studies

For the simulation the defined slot conductors of the FE-model were coupled with an external circuit and star- or delta-connected. A star connected ohmic load was included to simulate several operation points. To compare geometry versions and optimization steps among each other and the general concept with conventional alternators, three load states over the rotational speed were examined: the voltage in no load operation, the current in short-circuit operation and the absorbed power with a load of 1Ω star connected resistances. Furthermore the no load voltage over excitation current was calculated with regard to necessary voltage control in automotive on board applications. To verify the calculated results, they were compared to measured values and sufficient conformity was determined. Exemplarily the evaluation and comparison of voltages induced in star and delta connected alternator is presented. Due to third harmonics of the excitation field voltages are induced in the stator coils, which are not 120° phase shifted, but in phase. Currents result from these voltages if the alternator is delta-connected. These ring currents, just limited by relative small coil resistances, can reach high values, thus they counteract the third harmonics of the excitation field and nearly erase them. The resulted difference between the voltages as well as the conformity with measured values is illustrated in Fig 3. Furthermore the simulated currents in load operation and short-circuit operation were compared to measured values of the prototype.

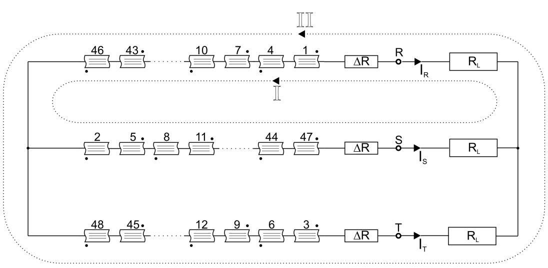

Fig. 2. Star connected alternator with ohmic load.

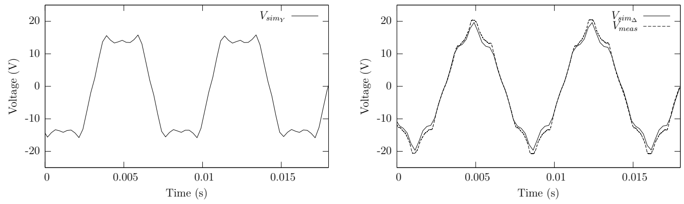

Fig. 3. Star- and delta connected alternator.

The geometry was optimized in various kinds. The embedding of the permanent magnet, the pole cover, the geometry of the excitation-winding slots was studied as well as the assembly of more than one magnet per pole. The final rotor geometry absorbed about 5% more power than compared Lundell alternator with equal stator. Furthermore the studied rotor was about 15% lighter because its axial length is that of the stator - in contrast to the Lundell type where the rotor length is more than twice of its active part.

See final paper for detailed and further results and evaluations.

V. Conclusion

Comparison with measurements on built prototype showed that the applied transient FE-simulation coupled with external circuit is suitable to simulate electrical machines in generator mode as well as the unknown stator currents with consideration of their reaction on the entire magnetic field of the machine. By that means it was possible to study, optimize and compare the hybrid excited alternator concept to conventional alternator designs before prototyping.

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