Study and geometry optimization of hybrid excited synchronous alternators for automotive applications

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Abstract— **Due to the increasing demand for on-board power a continuous development of automotive alternators concerning power, efficiency and power density is required. In this paper an alternative arrangement to conventional Lundell automotive generators is examined. This geometry is characterized by its hybrid excitation combining the high energy density of permanent magnets and the controllability of commonly used electrical excitation - thus a simple and cost-effective control of output voltage for application in on board supply systems is possible. A simulation of the alternator using the Finite-Element method (FEM) is performed to optimize the rotor geometry and to develop a design, ready for prototyping. The finite-element calculation of the alternator behavior and the unknown stator current, including their reaction on the entire magnetic field, requires a transient problem definition taking the geometry rotation into account. The FE model is coupled to an external electric circuit. The coupling with external circuit is exemplified in this paper. The accomplished studies, simulations and geometry optimizations are presented. All simulations are compared to prototype measurements and confronted with conventional alternator concepts. The developed geometry delivered about five percent more output power and was fifteen percent lighter compared to the Lundell alternator.**

I. Introduction

The automotive power supply required for electrical on-board equipment and charging the battery contains is usually realized by a clawpole (Lundell) alternator. Due to increasing power demand the alternators have to become more powerful and efficient. Thereby the increase of power is to be aimed at constant or even less installation space and weight. This requires a continuous development concerning power, efficiency and power density. Restricted improvement of the existing clawpole alternator leads to considerations on new and alternative design concepts.

An alternative machine design to Lundell type alternators, which are almost used exclusively for automotive power supply, is studied in this work. The alternative design consists of a hybrid excited rotor, 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 increased copper expense. With new magnetic materials featuring higher energy densities, improved temperature stability and reasonable prices, the application of permanent magnet excitation becomes more attractive. An important disadvantage of permanent magnet excitation is the missing possibility of field weakening, preventing appliance in automotive engineering previously. The gain of hybrid excitation is the combination of the high energy density of permanent magnets and the controllability of electrical excitation [1].

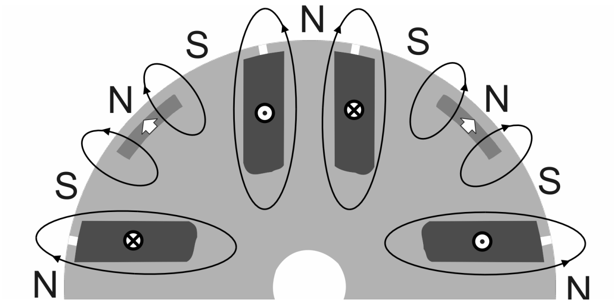


Fig. 1. Schematic geometry sector of examined rotor.

For this study the electromagnetic field and transient behavior of the generator is numerically simulated by the in-house FEM-software iMOOSE [2]. The transient behavior in short-circuit, no-load and load operation is simulated with coupled circuit simulation.

II. Studied geometry

In the present work a 16-pole geometry is analyzed. It consists of four electrical and four permanent magnet 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 the 'active' poles (Fig. 1). Used permanent magnets are rare-earth-magnets of NdFeB grades.

The actual pole number, and thus the behavior of the machine, depends on the excitation of the electrical poles. If the electrical excitation winding generates poles with the same

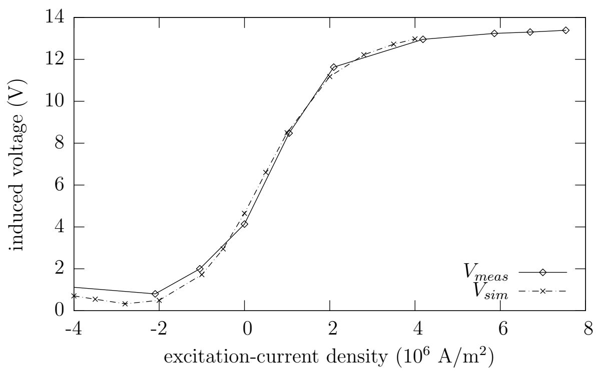


Fig. 2. Induced voltage versus excitation current at n=1000 rpm.

polarization as the permanent magnets, a symmetric 16 poles field is generated, induced voltage and delivered power are at a maximum under this conditions. Without electrical excitation the field has 8 asymmetric poles. Due to the asymmetry, the flux crossing the stator coils is unequal to zero, so the induced voltage is unequal to zero and power is generated. If the excitation current is negative, the course of the rotor field has 8 symmetric poles.

This behavior becomes apparent in Fig. 2 where the simulated and measured induced voltage versus the excitation-current density is plotted. In this study the speed of the machine is kept constant at 1000 rpm. Without excitation current the induced voltage is about 5V. By increasing the excitation current the induced voltage is increased linearly until the characteristics flatten due to the ferro-magnetic saturation. By increasing the excitation current in the opposite direction the induced voltage decreases until the 4-pole rotor field appears. In this case the induced voltage has its minimum value.

Therefore the output voltage of the generator can be controlled by the excitation current. However, the voltage control can not be effected by a conventional two-step control strategy, where the average excitation current is regulated by the on/off-time of periodic switching. Instead of that the control would have to switch between positive and negative excitation. The induced voltage and a possible output current even with no excitation current in the case of a machine fault has to be considered with respect to safety regulations.

At high rotational speed, where without excitation current a sufficient output voltage and current can be generated, an obvious decrease of the necessary excitation current can be assumed, so the overall efficiency is improved.

III. Accomplished studies

To simulate the alternator for particular 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 solution, which considers the geometrical rotation and which is coupled to an external electric circuit model. The applied in-house solver is part of an object-oriented solver package

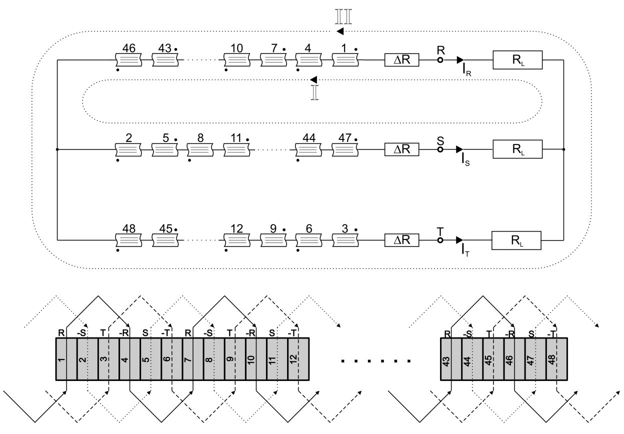


Fig. 3. Star connected alternator with ohmic load.

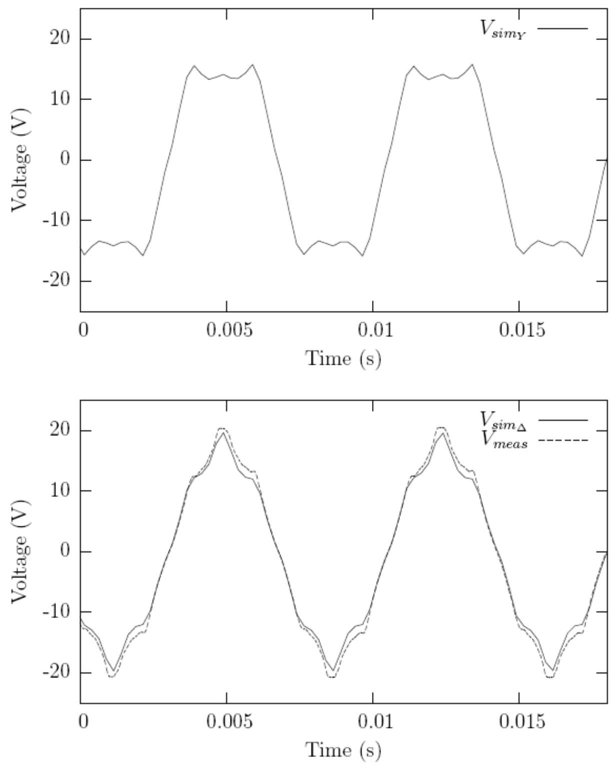


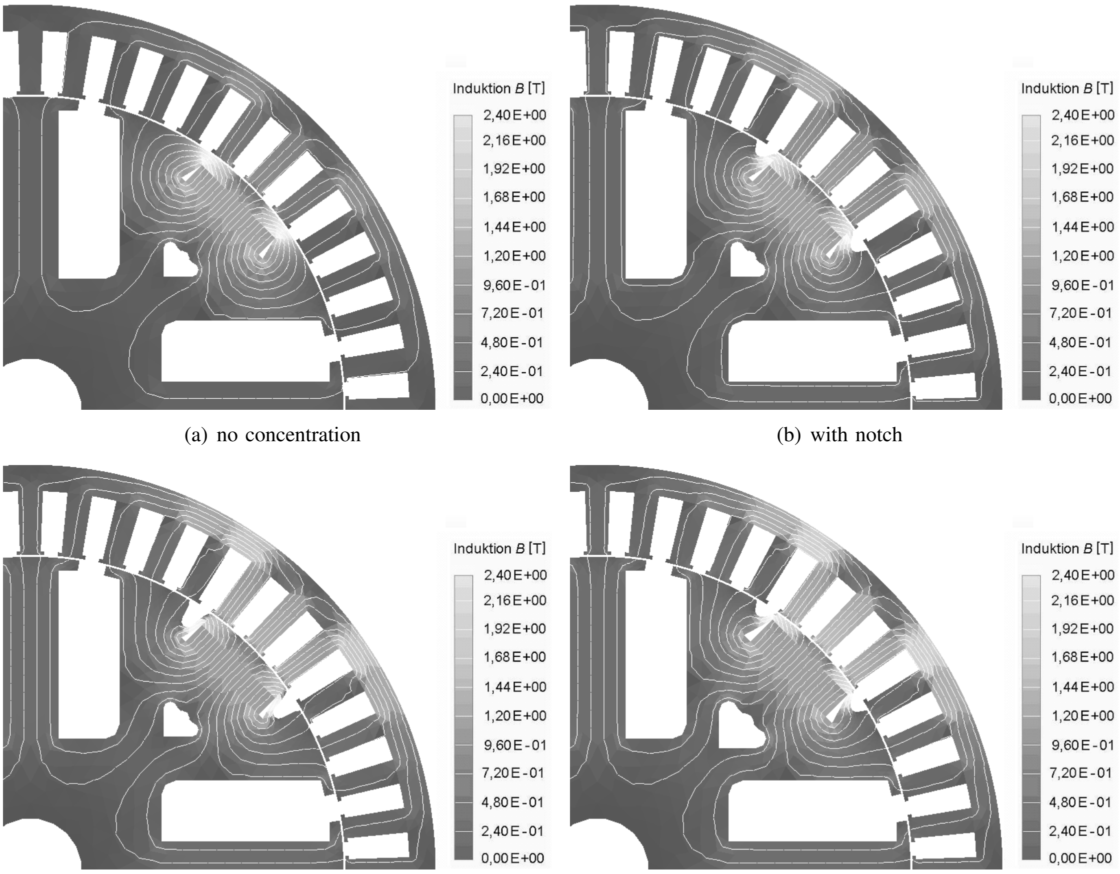
Fig. 4. Voltage of star- and delta connected alternator.

[2]. The transient FEM formulation considers the rotor displacement by means of time-stepping.

For the simulation the defined slot conductors of the FE-model were coupled with an external circuit model in star-respectively delta-connection. A star connected ohmic load was included to simulate the various operation points. To compare the geometry variations, the optimization steps and the hybrid concept with conventional alternators, three load states versus the rotational speed were examined: the voltage in no load operation, the current in short-circuit operation and the delivered power with a load of 1Ω star connected resistors. Furthermore, the no load voltage versus excitation current was calculated with regard to the required voltage control.

The simulated results were compared to measured data and showed a good agreement. Exemplary the evaluation and comparison of voltages induced in star and delta connected alternator is presented in this paper. Due to the third harmonics of the excitation field, voltages are induced in the stator coils, which are in phase. Currents result from these voltages if the alternator is delta-connected. These ring currents, limited by the small coil resistances, can reach high values, thus they counteract the third harmonics of the excitation field and nearly compensate them. The difference between the voltages as well as the conformity with measured data is shown in Fig 4.

The rotor geometry was optimized with respect to various considerations. The embedding of the permanent magnets, the pole arc and the geometry of the excitation-winding slots was studied as well as the assembly of more than one permanent magnet per pole. Additionally the influence of pole chamfer



(a) no concentration

(b) with notch

(c) wider notch

(d) increased pm-height

Fig. 5. Magnetic field depending on flux concentration.

was examined in regard to later acoustic noise optimization of the generator. Exemplary four of these accomplished studies are presented in the following section.

A. *Design of the embedded permanent magnets*

Automotive alternators are firmly coupled to the combustion engine, commonly with a 1:3 transformation of speed. So the rotor may be operated with speeds up to 18,000 rpm causing enormous material stress. For this reason the permanent magnets are buried in the studied machine. However, there is a disadvantage: because the magnet is entirely surrounded by ferromagnetic steel, the main part of the magnetic flux may close in the rotor - a magnetic short circuit. This flux neither cross the air gap nor the stator coils so it is not available for voltage induction. The flux linkage is approximately 44% (Fig. 5(a)).

By flux barriers (notches near the magnets) at the outer rotor radius, the area, available for magnetic short-circuit, can be reduced. Due to increasing saturation of this area, the magnetic resistance via air gap and stator will relatively decrease - therefore the magnetic flux will increasingly close through air-gap and rotor. However, the remaining permanent-magnet support must assure sufficient mechanical stability at high speed. A compromise between sufficient stability and efficient permanent-magnet use has to be found. Fig. 5(b) to 5(d) show steps of development in which the flux linkage was increased up to 75% in compliance with sufficient strength of the magnet support.

B. *Reducing of saturated areas*

Ferromagnetic saturation effects appear in the outer part of the rotor close to the excitation winding even for small excitation currents. Especially the area between the electrical excited and permanent magnet excited pole (area of return flux an opposite polarization) is not evenly pervaded. The air-gap induction is accordingly uneven as shown in Fig. 6.

Rounding the coil (also compare Fig. 5 and Fig. 7) affects the flux in such a way that there is sufficient material for the return flux available. Therefore, the air gap induction becomes more symmetric and even. The homogenization of the air gap induction leads to a slight increase of the induced voltage. At the examined speeds a gain of delivered power is obtained. In the range of lower speed the power gain is larger. At higher speed ferromagnetic saturation of the rotor is not important due to the field weakening effect of the armature reaction of the stator current. Table I shows the relative power gain for exemplarily chosen speeds.

C. *Design with regular pole cover*

The previous rotor design had an irregular pole cover. The electrical excited poles covered an angle of 18°, the

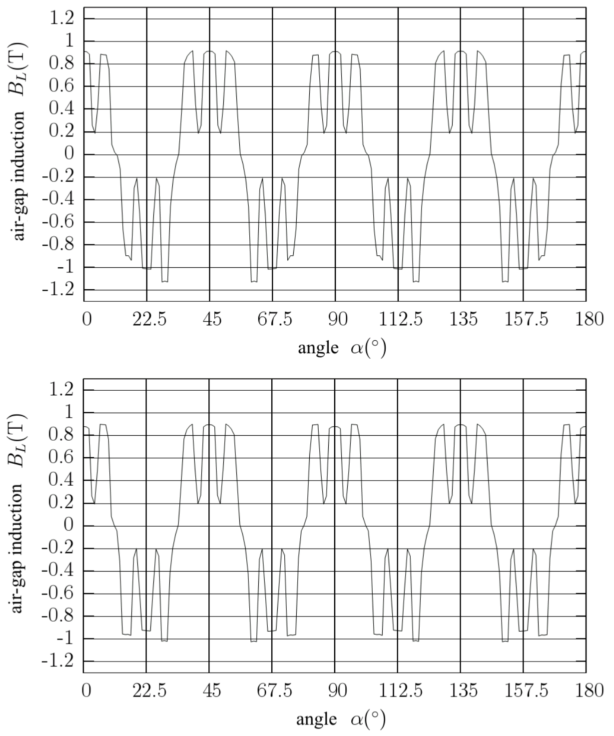


Fig. 6. Air-gap induction before and after rounding the coil frame.

TABLE I
DELIVERED POWER WITH AND WITHOUT ROUNDING THE COIL FRAME.

	speed (rpm)		
	1000	3000	6000
without rounding (W)	149	1314	4999
with rounding (W)	161	1328	5046
difference (%)	+7.93%	+1.10%	+1.55 %

permanent-magnet excited poles an angle of 20° and the poles produced by the return flux an angle of 16°. The spaces between the poles were dimensioned to 5°.

To study the influence of the irregular pole cover, the rotor is designed with a regular pole cover and the simulated results are compared. All poles cover an angle of 18° in this case; the interpolar gap covers an angle of 4.5° . The pole cover is also visible in the course of the air gap induction - by the regular pole cover a better symmetry is obtained. Due to the smaller permanent-magnet excited poles the average flux linkage produced by each pole decrease about 3%. Therefore, the induced voltage decreases and the possible current and power under load condition decrease as well.

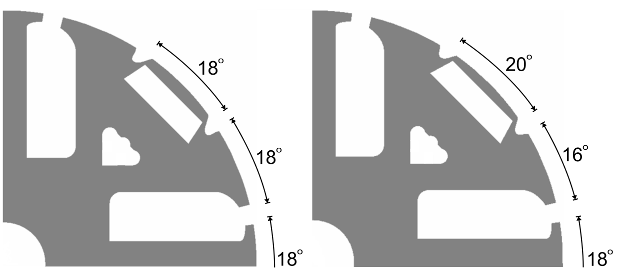


Fig. 7. Geometries with regular and irregular pole cover.

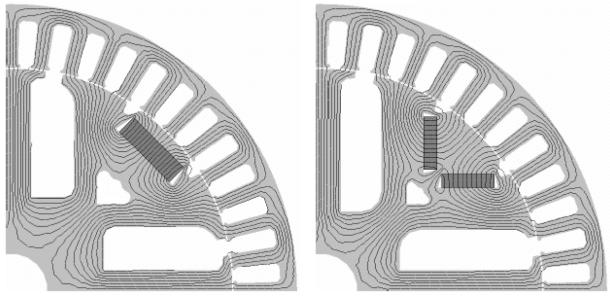


Fig. 8. Geometries with one and two permanent magnets per pole.

With an additional examination of the torque spectrum it becomes obvious that the cogging torque depends on the pole cover. The Cogging torque is larger with regular pole cover, although magnet dimensions are smaller and less flux is generated. With regular pole cover the cogging torques act in the same time and rotational position, so the cogging torques produced by each pole are added to one total torque.

If the poles are irregular the single forces act at different rotor positions and the total torque of the rotor is smaller. A reduction of cogging torque can be obtained with the irregular pole cover. A further reduction of cogging torque would be interesting for reducing acoustic noise problems and can be reached with a skewed rotor or stator. This is not examined in this work.

D. Design with two permanent magnets per pole

Instead of a single magnet per permanent-magnet excited pole, two magnets can be used in v-form arrangement (Fig. 8). This arrangement leads to an enlargement of available magnet area and permit a higher magnetic flux. But it also requires an adjustment close to the excitation windings due to the early occurrence of saturation between the winding and the magnet. For this reason the coil areas are designed narrower. To keep the size of the area, the coil areas are extended by the same factor. Two attempts were examined in this work: first, to reach the same useable flux with fewer permanent-magnet material and second, to reach an increased output power with constant magnet material.

In the first case a design was found that reaching the same flux with only half of the material. A comparison of the simulation results shows the same induced voltage, but an decreased maximum current (about 7%). In the second case the area of the single permanent magnet was divided into two magnets. With this arrangement a flux linkage 8% higher than the previous one was obtained. Due to the larger useable flux linkage the induced voltage increases about 5%, the maximum current increases about 12.4%. Depending on the speed there are power gains of up to 13%. Performed studies show, that it is possible either to save permanent-magnet material or to generate a higher output power with the same material quantity - production expense of inserting the magnets would nearly be constant. However, it has to be considered, that due to the higher magnetic flux the already high cogging torque will increase further.

IV. Results and comparison of rotor types

To ensure a well comparability, the simulations of all rotor types were accomplished with the same number of poles and identical stator geometry and interconnection respectively. This stator was part of a Lundell-type alternator and was also used for prototyping of the studied hybrid machine design.

In Table II the simulated data of delivered output power are presented for particular rotor speeds. Compared geometries are the studied design (K16), a salient pole synchronous machine (SPSG) and the Lundell-type alternator. Presented versions of studied geometry are the design used for prototyping and two further developments: one with improved geometry with respect to magnetic saturation (K16-W), the other design featuring two magnets per pole (K16-2PM). The final rotor geometry (K16-2PM) delivered about 5% more electrical power compared to Lundell alternator with identical equal stator.

Comparing the weights of the different rotor geometries indicates that the studied rotor was about 15% lighter in weight. This is due to its axial length - in contrast to the Lundell type where the rotor length is more than twice of its stator. The weights collected in Table III are the weights of the active machine components such as stator, rotor and windings. Other components like the casing are neglected, because they are the same for all studied rotor geometries as mentioned before. Due to the less weight and higher power the power density of the studied geometry is about 14% higher.

The simulated short-circuit currents of the studied geometries are compared in Fig. 9 . The design used for prototyping (K16) reached a short-circuit current of 149.6A. The final geometry (K16-2PM) featuring two permanent magnets per pole reached a current of about 160A and was therefore 6.6% higher. The salient pole synchronous machine (SPSG) provides the lowest short-circuit current of about 112.8A.

TABLE II
Simulated values of delivered power.

	delivered power (W)		
	1000rpm	3000rpm	6000rpm
K16	155	1019	4999
K16-W	161	1328	5046
K16-2PM	159	1404	5334
SPSG	88	788	2998
Lundell	147	1323	5043

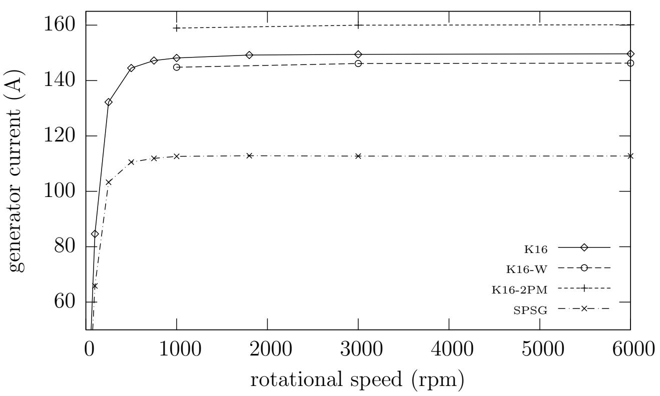


Fig. 9. Simulated short-circuit current.

TABLE III
Power density of compared geometries.

	power (W)	weight (g)	power/weight (W/kg)
K16	4999	4335	1153
K16-W	5046	4333	1165
K16-2PM	5334	4362	1223
SPSG	2998	4456	673
Lundell	5043	4781	1055

V. Conclusion

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. To simulate the generator in different operation points, a Finite-Element model is applied taking the rotating geometry into account. The FE model is coupled to an external electric circuit model. Comparison with measurements on a prototype showed that the applied transient FE-simulation coupled to external circuit is suitable to simulate electrical machines in generator mode and to calculate 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. The finally developed geometry generated about five percent more power, but the weight was reduced by fifteen percent compared to the Lundell generator.

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