Numerical Procedures for the Calculation and Design of Automotive Alternators

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***Abstract*— Numerical procedures were developed for the calculation and design optimization of claw-pole alternators. Based on the three-dimensional (3D) magnetostatic field computation the output performance, efficiency, local and global forces are computed and compared to measurements. The precalculation of a claw-pole alternator is presented on the example of a prototype with additional permanent magnets.**

I. Introduction

The claw-pole alternator is the oldest type of three-phase electrical machine and is a special kind of synchronous machine. The first one was used in 1891 to generate electricity for the first three-phase transmission line from Lauffen to Frankfurt/Main in Germany. Later most generators were constructed as salient-pole or turbo machines and the claw-pole type disappeared from the field. From the beginning of the 1960th there was a revival of the alternator for the generation of electric power in vehicels and especially in automobiles.

Today millions of alternators are produced at a very high level of automization. Although the production costs are very low, every improvement that increases the output performance or the efficiency has to be implemented. This is necessary because the number of small drives and electronic components increases all the time to make the cars safer and more comfortable. The intention of this paper is to present reliable numerical methods for the precalculation of the alternator to replace the classical optimization method that uses hardware samples.

II. Calculation methods

The main part of numerical calculation is to describe the terminal behaviour of the alternator. Actually there are three major tasks dealing with the following topics:

- The output performance has to be increased,
- the losses should be reduced and the efficiency improved,
- the forces and the audible noise have to be reduced.

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In the following subsections three different procedures are described which are helpful to gain these targets or to come closer to them. All methods base on the magnetostatic field calculation which is introduced at first.

A. Calculation of magnetostatic field and performance

The shape of the claws leads to a truly 3D magnetic field in all regions. Moreover the claw's geometry has to be modelled as accurate as possible because of the large influence on the output performance of the alternator. The magnetically relevant parts are shown in figure 1. The solid rotor consists of two claw-pole wheels, the core with circumferrential exciting coil and the shaft. The stator is laminated (1mm thick steel sheets) and carries the three-phase winding.

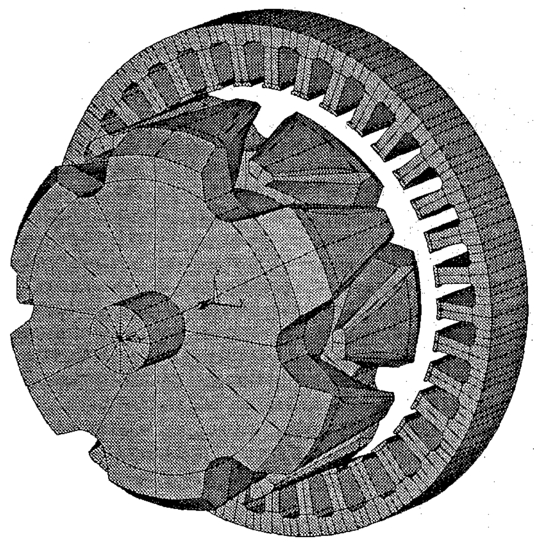

Fig. 1. Geometry of the claw-pole alternator

While constructing the Finite Element mesh, symmetry and periodicy are taken into account. So only one pole of the alternator has to be modelled. Figure 2 presents a typical model without coils and surrounding air. Usually one FE mesh, representing one single position of rotor versus stator, gives good results for the fundamentals of air-gap induction, stator flux linkage and induced voltage. After calculation of magnetostatic field the on-load behaviour at any speed can be determined iteratively using the vector diagram of the salient-pole synchronous machine [3].

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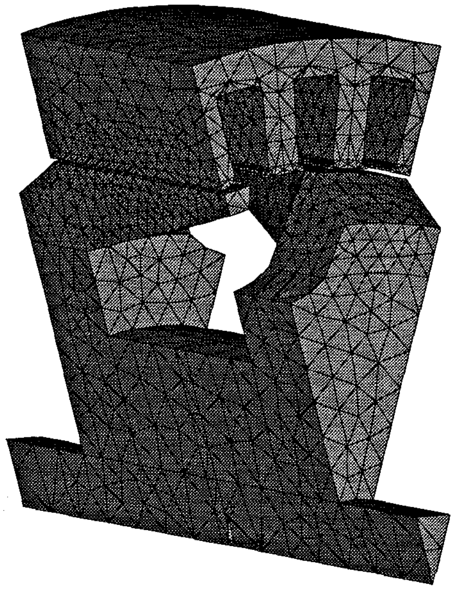

Fig. 2. FE mesh of one pole-pitch

Three different alternators with different outer diameters, different shapes of the claws and different output performances were investigated and compared to measurements. Usually the design engineer is interested in the no-load and the load characteristic of the machine. The load characteristics (DC output current I_g vs alternator speed n) are plotted in figure 3.

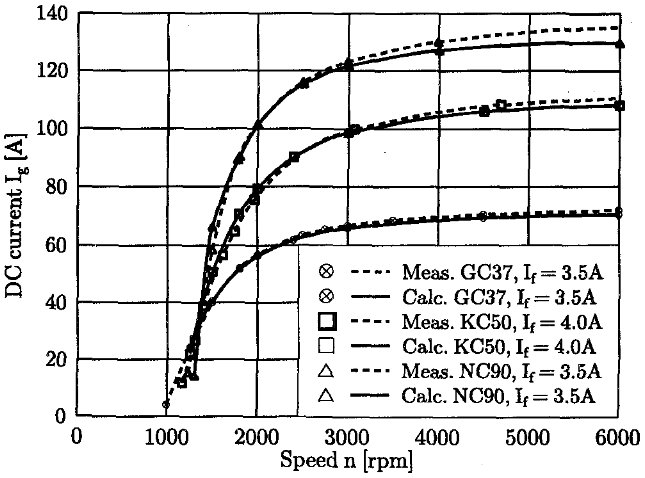

Fig. 3. Load characteristics of different alternators

The presented procedure is very useful to get the DC value of the output current I_g and the rms values of voltage U_1 and current I_1 on the three-phase side. The effect of rectifier bridge is taken into account via two correction factors for current (k_i) and voltage (k_u) as derived in [8]:

$$k_i = \frac{I_g}{I_1} = \frac{3}{\pi} \cdot \sqrt{2} \cdot \cos\varphi_1 \approx 1,35 \cdot \cos\varphi_1 \ , \quad (1)$$

$$k_u = \frac{U_B}{U_1} = \frac{1}{\frac{\sqrt{2}}{\pi} + k_D \cdot \frac{U_T + R_B \cdot I_1}{U_B \cdot \cos\varphi_1}} \ . \quad (2)$$

The variables I_1 and U_1 represent the fundamentals of current and voltage, $\cos\varphi_1$ is the power factor, U_B=13.5 V the battery voltage, k_D a correction factor, $R_B = 4.3\ m\Omega$ the bulk resistance and U_T=0.6 V the threshold voltage of the diodes. The time functions of voltage and current can be simulated using a simple machine model [7].

B. *Calculation of efficiency*

The second calculation procedure deals with the determination of losses and efficiency. The losses are separated as accurate as possible. For all calculations the alternator is supposed to be seperatly excited. The basic losses are the mechanical ones, the copper losses in the stator coil, the losses of the rectifier bridge and the iron losses in stator and rotor. The rating chart (figure 4) illustrates the flux of power.

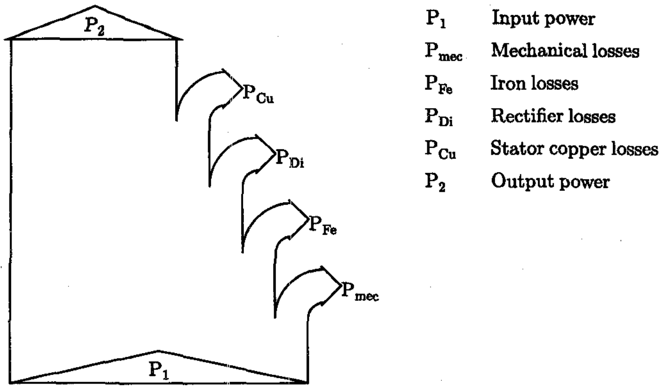

Fig. 4. Rating chart of the alternator

The mechanical losses can be measured at the operation without any exciting current. Empirical studies of different alternator types and comparison to classical formulations [1] lead to the expression of (3) with one portion depending on the bearings (P_{Be}) and another one depending on the ventilator (P_{Ve}). The copper losses in the stator coil (4) and the rectifier losses (5) can be computed very simple. The factor $k_D = 1.14$ includes additional commutation losses of the diodes.

$$P_{mec} = P_{Be} \cdot \left(\frac{n}{n_0}\right)^{1,5} + P_{Ve} \cdot \left(\frac{n}{n_0}\right)^3 \quad (3)$$

$$P_{Cu} = 3 \cdot R_1 \cdot I_1^2 \quad (4)$$

$$P_{Di} = 3 \cdot k_D \cdot (U_T + R_B \cdot I_1) \cdot I_1 \quad (5)$$

The main problem is the determination of iron losses in the solid claw-poles. Slotting harmonics of the air-gap field induce eddy currents into the claws. The calculation of these currents requires a time-step calculation procedure with a very short time-step, but the computation time is much too high yet. For that a simple equivalent model was developed to examine the way of eddy currents. It was found out that the ratio of iron losses (rotor to stator) is about 2:1.

The loss distribution was checked on a standard alternator with original claw shape. The output current, copper losses in stator, rectifier losses and the iron losses in the stator $P_{Fe,S}$ were calculated, the mechanical losses and the mechanically supplied power were measured. From the power rating the rotor iron losses $P_{Fe,R}$ may be subtracted as follows in (6). The ratio of 2:1 from rotor to stator iron losses was verified. Because of that fact the total efficiency can be approximated as shown in (7).

$$P_{Fe,R} = P_1 - P_2 - P_{Cu} - P_{Di} - P_{Fe,S} - P_{mec} \quad (6)$$

$$\eta \approx \frac{P_2}{P_2 + P_{Cu} + P_{Di} + P_{mec} + 3 \cdot P_{Fe,S}} \quad (7)$$

The diagram of performance and losses of the test alternator (P_2=1.5 kW) is plotted in figure 5. The efficiency increases to 64% (2000 rpm) and decreases to about 40% at higher speeds. Note that the efficiency is reduced by about 2% if the alternator is self-excited because of copper losses in the field coil.

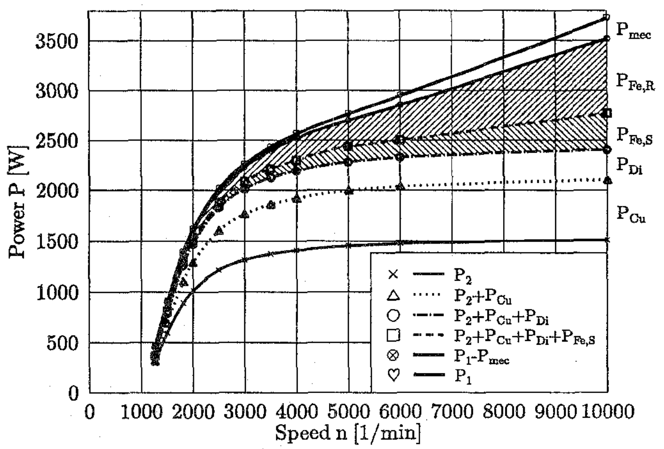

Fig. 5. Power and losses of the alternator vs speed

C. *Calculation of forces*

From the magnetostatic field calculation the surface force density distribution is calculated using Maxwell's stress tensor (8 and 9). The force density σ follows from the normal component H_n in region 1 and 2 on both sides of the boundary surface. The normal vector is called $\vec{n}_{12}$, the magnetic cooenergies which have to be computed from the field quantities are called w_1' and w_2'. The method was presented in [5] on the example of an induction furnace and was applied to the claw-pole alternator [6].

$$\vec{\sigma} = \Big((H_{1n} - H_{2n}) \cdot B_n - (w_1' - w_2') \Big) \cdot \vec{n}_{12} \quad (8)$$

$$\text{with} \quad w_1' = \frac{1}{2} \cdot (\vec{H}_1 \cdot \vec{B}_1)\ , \quad w_2' = \frac{1}{2} \cdot (\vec{H}_2 \cdot \vec{B}_2) \quad (9)$$

From a number of 5 FE models, each representing one single point of time and one special stator-rotor-position, the time functions of induction and force-density at each node are computed. The integration about surface yields the forces which can be interpolated onto a full mechanical model of the machine. These forces cause the mechanical vibrations. The procedure works, but the investigation of mechanical material parameters is not finished yet. So only global forces will be presented in this paper.

The spectra of radial and tangential forces working on a single stator tooth are shown in figures 6 and 7. At no-load the DC value of radial force is maximum and the tangential one disappeares. The DC component of radial force decreases with speed because of the armature reaction, the tangential one is maximum at about 2400 rpm. Because the tangential force is proportional to torque, this is the speed of maximum torque, too. It can be seen that the most spectral components behave similar.

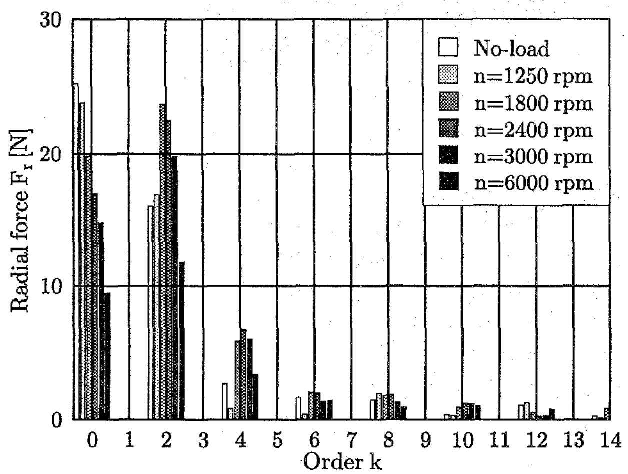

Fig. 6. Spectrum of radial forces on a single stator tooth

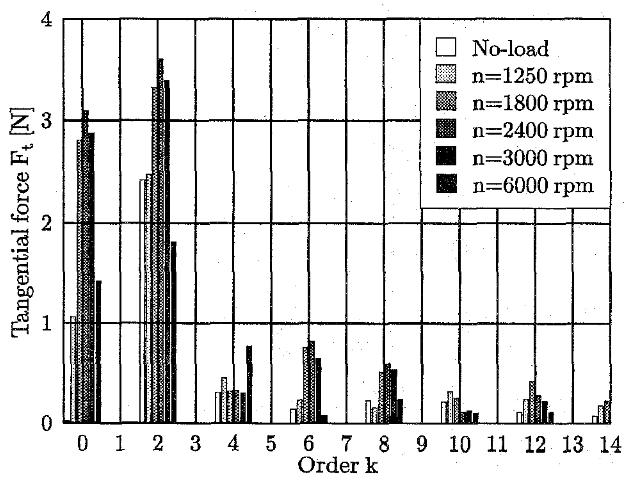

Fig. 7. Spectrum of tangential forces on a single stator tooth

Equation 8 yields that the frequencies of the fundamental and harmonics of forces are double as high as the frequencies of induction components. Therefore the spectra have only even orders of force. Another interesting point is that the values of tangential forces reach only from one tenth to one fifth of the radial ones. From the tangential forces the torque can be computed.

III. Results of optimization

A. Design optimization

Several aspects were investigated to improve the output performance of the alternator. One method is to optimize the shape of the claws using the FEM and the Response Surface Method [2]. The calculation time to compute the load characteristic is about one day per sample on an hp755 workstation. So only a few parameters may be optimized simultaneously. It was shown that the output performance can be improved by 20% while changing the pole-pitch and the flank angle of claws [8].

B. Additional permanent magnets

The application of additional permanent magnets is another method to improve the output performance. Several variants with different magnet positions were investigated to find the optimum effect on performance. The permanent magnets may operate actively increasing the total flux passing the rotor or they compensate one part of the leakage flux that passes between the claws.

Some disadvantages of the active principle were reported in [4]. As the permanent magnets excitation is continous, the voltage controller would have to be modified to weaken this field at higher speeds. Additionally the required level of flux is so high that only rare-earth materials could be implemented. The best position of magnets is at the surface of the claws, but there are problems of fixing the magnets and of high temperature level.

The compensation principle is the better one and was investigated more in detail. The leakage flux between the claws amounts about 30% of the main flux at the position of core at no-load condition and may increase to about 50% under full load. So the best position of magnets is between the claws to compensate this leakage flux [4], [8]. The rotor model of this variant is presented in figure 8. Simple ferrites (SrFe) can be used and the voltage controller remains unchanged.

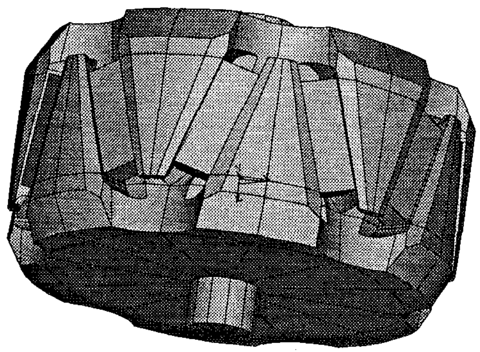

Fig. 8. Rotor with additional permanent magnets

The improvement of performance versus speed is shown in figure 9. The precalculated and measured values agree very close. The output performance increases by about 40% at lower speeds and 5% at higher ones. Furthermore there is a good correspondence to the demands of typical driving cycles.

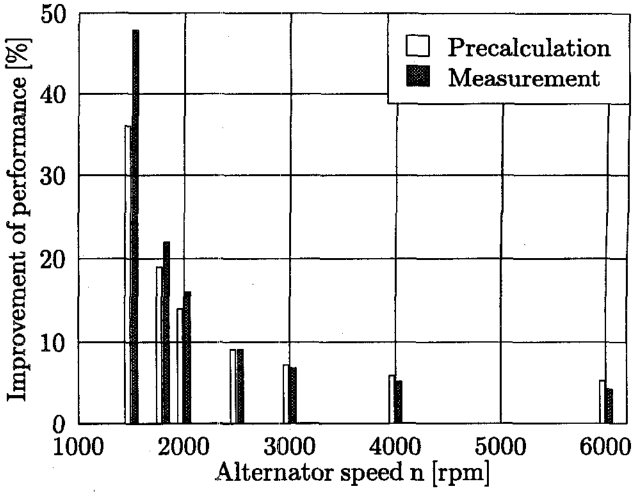

Fig. 9. Improvement of the output performance vs speed

IV. Conclusion

Numerical procedures for the calculation of automotive alternators were presented. The rms values of terminal voltage and current can be computed with a maximum error of 5%. A procedure to separate losses and to predict the efficiency was developed. Force density distribution and global forces on rotor and stator were investigated and can be used to calculate displacements and audible noise in the future. For the first time it was shown that the output performance of a new type of claw-pole alternator can be precalculated accurately.

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