Analytic modelling of automotive claw-pole alternator for design and constrained optimisation

Laurent ALBERT [*+], Christian CHILLET [*], Antoine JAROSZ [+], Frédéric WURTZ [*]
[*] Laboratoire d'électrotechnique de Grenoble
ENSIEG – BP 46, 38402 Saint Martin d'Hères, France
laurent.albert@leg.ensieg.inpg.fr, christian.chillet@leg.ensieg.inpg.fr, frederic.wurtz@leg.ensieg.inpg.fr
[+] PSA-Peugeot-Citroën
18, rue des Fauvelles
92256 La Garenne Colombes, France
antoine.jarosz@mpsa.com

Keywords – Modelling, Design, Generation of electrical energy, Automotive components

ABSTRACT

Most of car alternators are claw-pole synchronous machines with poor efficiency. A Claw-pole alternator computer design strategy is presented in this paper. First, a model based on magnetic equivalent circuit and first harmonic electric scheme is established. Then, initial volume remaining constant, this model is implemented into an optimisation software to improve the alternator efficiency.

INTRODUCTION

The constant rise of the overall onboard electrical power compels automotive manufacturers to optimise energy storage and supplying systems. The main difficulty of future years is to mix electrical functionalities of increasing complexity, taking into account : operational safety, pollution, comfort and life expectancy.

Besides, the behaviour of several electrical devices remains misunderstood. Because of complex chemical phenomena, the simulation of lead acid battery is too rough to allow an optimised management of onboard energy. The alternator, a claw-pole machine linked with a three-phase rectifier bridge, is also very difficult to model. At the present time, the efficiency of onboard electricity generation is so low (about 50 %) that an increase of this figure is conceivable. This paper shows, therefore, a strategy to model and optimise a claw-pole alternator using magnetic equivalent circuits.

Because of 3D paths of magnetic fluxes, claw-pole alternator models are complex. This machine is a three-phases synchronous generator. Two rings of 6 or 8 claws surround the excitation coil and the core. The armature flux generated by the excitation coil flows first axially in the core, then goes up into the claws, crosses the air-gap, enters the laminated stator before returning to the opposite claws and the core. This special kind of rotor allows to get a magnetic field with a high number of poles, using only one coil.

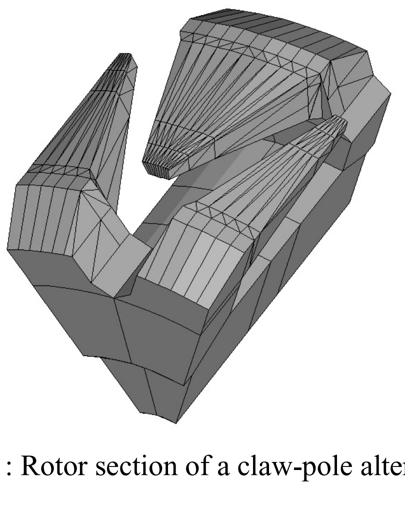

Fig. 1 : Rotor section of a claw-pole alternator

At the present time, an optimisation process based on the 3D finite element methods seems to be impossible because of computation capability limitations.

Thus, models presented in references [1] and [2] seem to be good for accurate simulations, but they are unsuitable for optimisation. Other models introduced in references [3], [4] and [5], use Magnetic Equivalent Circuit (MEC). The one presented in reference [5] seems to be a better compromise between accuracy and time computation constraints. But, due to numerous parameters, an optimisation process based on this approach seems to be difficult to perform. The model presented in [4] uses MEC built with 3D FE computations, geometric optimisation becoming thus impossible. Finally, the model presented in [3] is interesting because based on simplified MEC, but the model of armature reaction and electrical circuit seems to lack of accuracy.

As a result, an analytic model using a simplified MEC seems to be more suitable to perform optimisation. The alternator model presented in this paper is divided in three parts. Firstly, the three-phase rectifier bridge is modelled using the first harmonic hypothesis. Then, a magnetic model is created based on MEC method. Finally, these two models are merged together, using electromagnetic coupling.

MODELLING

ELECTRICAL MODEL

Above 3000 rpm, the phase currents of a claw-pole alternator are closed to a sinus wave. That's why a first harmonic model of the three-phase rectifier bridge is accurate enough to compute power output. The electric circuit model developed here is based on the work of V. Caliskan [6]. The electromotive forces delivered by the alternator (e_a , e_b and e_c) are assumed to be sinusoidal. Furthermore, the three-phase bridge rectifier is substituted by equivalent resistors, because machine currents and phasor voltages are in phase (Fig. 2).

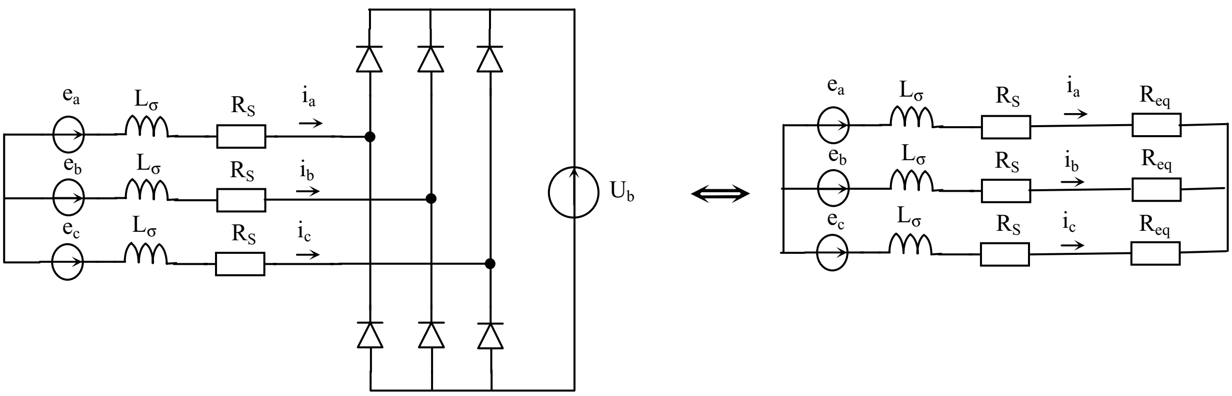

Fig. 2 : Claw-pole alternator electric circuits
exact model (on the left) and first harmonic model (on the right)

The analytical expression of these resistors [6] is :

$$R_{eq} = \frac{\left(\frac{4V_0}{\pi}\right)^2 R_S + \left(\frac{4V_0}{\pi}\right)\sqrt{(\omega L_\sigma)^2\left[\left(\sqrt{2}\,E_R\right)^2 - \left(\frac{4V_0}{\pi}\right)^2\right] + R_S{}^2\left(\sqrt{2}\,E_R\right)^2}}{\left(\sqrt{2}\,E_R\right)^2 - \left(\frac{4V_0}{\pi}\right)^2} \quad \text{(Eq. 1)}$$

With: $V_0 = \frac{U_b}{2} + V_d$ (half of battery voltage plus drop voltage of a diode).

E_R : RMS value of electromotive forces (defined by electromagnetic coupling).

R_S : One phase Resistance (defined by an analytical expression).

L_σ : Leakage inductance of one phase (defined by an analytical expression).

ELECTROMAGNETIC COUPLING

Electromagnetic coupling is realised using a phasor diagram. A claw-pole alternator is a salient-pole synchronous generator, with high saturated areas. Hence, the armature reaction is modelled thanks to the Blondel phasor diagram approach. This reaction flux is separated into two components expressed in the Park reference frame (d-axis and q-axis). The model synopsis and the phasor diagram are showed in Fig. 3 and Fig. 4.

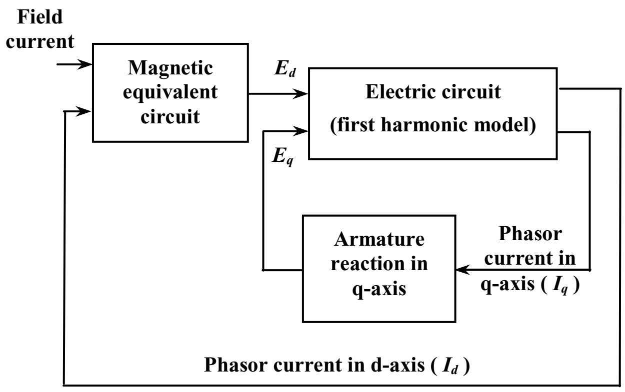

Fig. 3 : Claw-pole alternator model synopsis

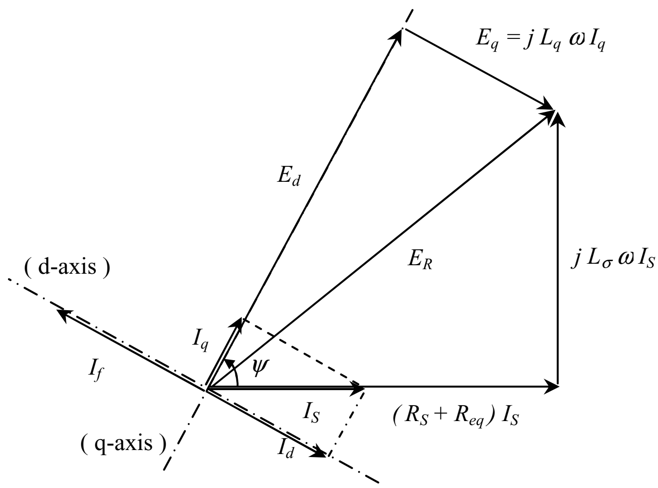

Fig. 4 : Blondel phasor diagram

MAGNETIC MODEL

ARMATURE REACTION IN Q-AXIS

In a large range of speeds and loads, the load angle Ψ is around 90 degrees, and so the phasor current in q-axis is low. As a consequence, iron saturation is low and q-axis inductance (L_q) is assumed to be constant. This parameter is deduced from the air gap geometry.

ARMATURE REACTION IN D-AXIS AND FIELD CURRENT EFFECT

In d-axis, iron saturation is important, so that a magnetic equivalent circuit is built in order to get magnetic fluxes (Fig. 5).

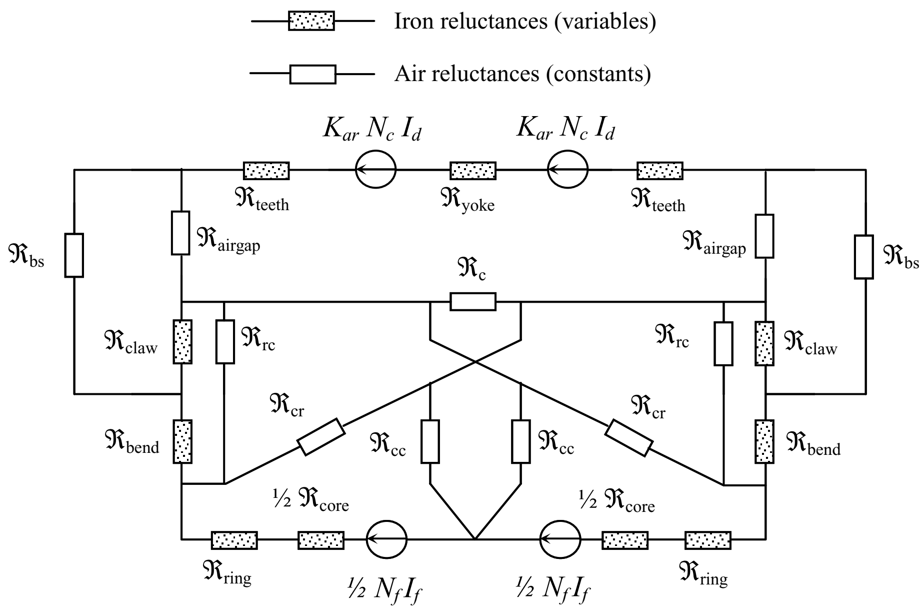

Fig. 5 : Claw-pole alternator magnetic equivalent circuit

The magnetic field is produced using a coil of N_f turns, that is supplied by the field current I_f.

Every iron reluctance is a non-linear function of the flux. All the reluctances are calculated using analytical formula. This is necessary because reluctance analytical expressions allow a linkage between geometric parameters and magnetic fluxes. Thus, an optimisation process (sizing process) can be performed.

Here is an example of iron reluctance expression : $R_{core}(\Phi_{core}) = \frac{L_{core}}{\Phi_{core}} H\left(\frac{\Phi_{core}}{S_{core}}\right)$

With : Φ_{core} : magnetic flux in the core.

L_{core} : flux path average length in the core.

S_{core} : core section area.

H (B) : analytical function giving field versus induction, taking into account saturation effects.

This reluctance network takes account of many leakage fluxes. Here is the list of air reluctances corresponding to leakage fluxes:

R_c : leakage reluctance between two adjacent claw.

R_{rc} : leakage reluctance between a ring and the claw above it.

R_{cr} : leakage reluctance between a claw and the opposite ring.

R_{cc} : leakage reluctance between a claw and the core.

R_{bs} : leakage reluctance between a bend and the side of the stator.

A source of equivalent ampere turns simulates armature reaction, whom expression is : $K_{ar}\ N_c\ I_d$, where N_c is the number of wires in a slot, I_d is the phasor current in d-axis and K_{ar} is a coefficient taking into account the variation of armature reaction, according to claw geometry.

EXPRESSION OF ARMATURE REACTION COEFFICIENT (K_{ar})

Ampere turns created by the three phases are assumed to be sinusoidal. If we choose θ as the angular position to the d-axis, then amperes turns in d-axis could be described by the following formula :

$AT_d(\theta) = \frac{3}{\pi} N_c\ I_d\ \cos(p\ \theta)$ where p is the pole pair number.

Iron permeability is supposed to be infinite. Magnetic induction in d-axis in the air gap could therefore be given as :

$B_{airgap\ d}(\theta) = \mu_0 \frac{AT_d(\theta)}{e}$ with e as the air gap length.

Magnetic flux is defined by $\Phi = \int B\ dS$, so flux in d-axis created by armature reaction could be written as :

$\Phi_d = \int_{-\theta_2}^{\theta_2} R\ l(\theta)\ B_{airgap\ d}(\theta)\ d\theta$, leading to :

$$\Phi_d = \frac{6\,\mu_0\ R_R\ L_c\ N_c\ I_d\ \left(\cos(p\ \theta_1) - \cos(p\ \theta_2)\right)}{\pi\ e\ (\theta_2 - \theta_1)\ p^2} \quad \text{(Eq. 2)}$$

with R_R as the rotor radius and L_c as the claw length.

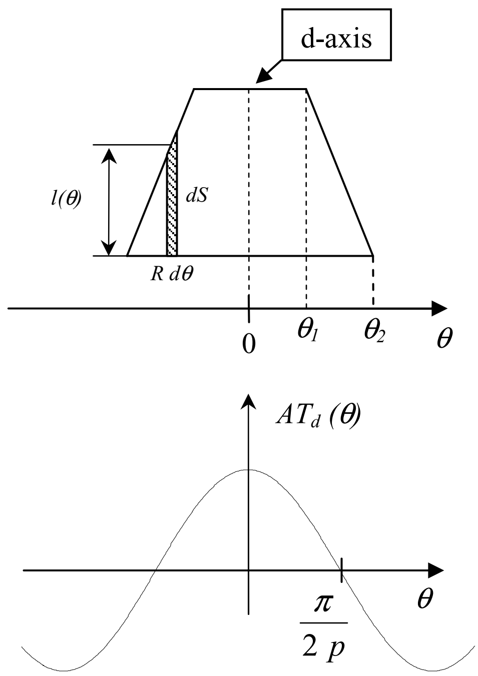

Fig.6 : claw surface (top figure) and ampere turns in d-axis (bottom figure)

The MEC (Fig. 5) gives, considering the same hypothesis : $\Phi_d = \frac{K_{ar} \; N_c \; I_d}{R_{air\,gap}}$ (Eq. 3)

Finally, equations 2 and 3 lead to the final expression of K_{ar} : $K_{ar} = \frac{6\left(\cos(p\,\theta_1) - \cos(p\,\theta_2)\right)}{\pi\,(\theta_2 - \theta_1)\,(\theta_2 + \theta_1)\,p^2}$

LOSSES MODEL

The model described above must be linked with losses computation, in order to get alternator efficiency. The losses considered are : copper losses, stator and rotor iron losses, bridge rectifier losses, field circuit losses and mechanical losses.

RESULTS

NO LOAD CASE

Model computation and measurements of a claw-pole alternator have been investigated here. Electromotive force at no-load is plotted versus field current (Fig. 7). Solid line shows model results, whereas cross points are experimental measurements. The model is accurate enough in the linear part of the curve and presents a small deviation in the non-linear part (3% with I_f = 4.2 A)

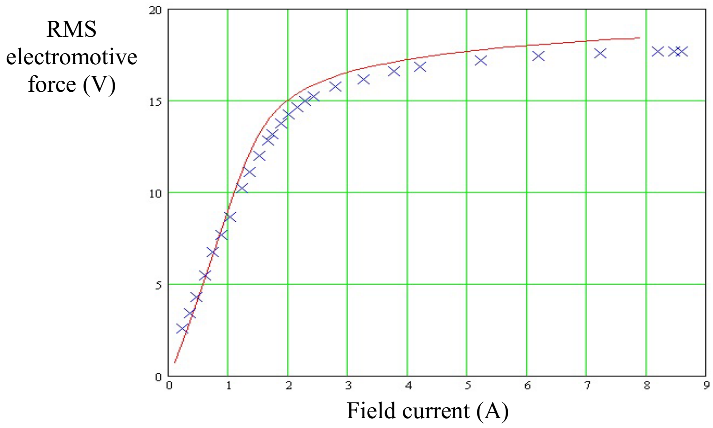

Fig. 7 : No-load electromotive force versus field current at 3000 rpm

LOAD CASE

Model is computed with maximum field current. Like above, solid line shows model results and cross points are experimental measurements. As shown in Fig. 8, there is a difference between measurements and analytical results (6% at 15000 rpm and 12% at 6000rpm). This difference is due to the difficulty to model correctly leakage inductance, especially in end windings. Moreover, the first harmonic model of the rectifier is less accurate at low speed, because of discontinuous conduction.

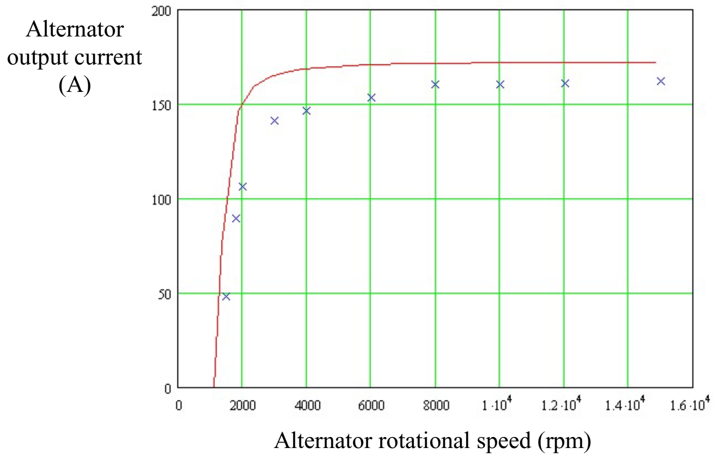

Fig. 8 : Alternator average output current at full load

The improvement of the model accuracy is still under investigation, but, in a first draft, deviations between model results and measurements are not compulsory when proving the feasibility of the optimisation process. The design performed hereafter shows trends that would be probably the same with a more accurate model.

SIZING AND DESIGN

Today, electric device designers have to handle an increasing number of constraints, like economic cost, size, EMC standards... The exploration of the entire solution space is thus becoming impossible with a try-and-cut methodology. Pro@Design software [9] uses the methodology described in [7] and is based on the software architecture of [8]. It is a generic software for the sizing and design of devices based on gradient optimisation. This software uses analytic models and symbolic partial derivatives, resulting in low CPU times (to the opposite of FE simulations). Therefore, solution space is explored in a more efficient way and an optimum may be found very quickly.

The model described in this paper is suitable to be used with this kind of software. All analytical expressions, along with cost functions, have been implemented in this software. The complexity of the model is high, because there are 22 functions, used to compute 116 equations with 63 input parameters, giving 116 output parameters. Moreover, the model uses 12 implicit equations, which gives 12 implicit parameters, because of non linearity of magnetic material and electric circuit. Thus, several kind of sizing process can be performed. Efficiency or power mass ratio can be optimised, taking indifferently the same geometric constraints into account in both cases.

In this paper, two optimisations are described, corresponding to two working points. The first working point is for "full load at 6000rpm" and the second is for "full load at 1300rpm". These two sizing processes have the same goal : to maximize efficiency with constant power output and sizing constraints. A high number of parameters (30 with implicit parameters) are optimised together, like geometric parameters, number of coil turns and wire area. Furthermore, 32 output parameters have been constrained in order to define a feasible alternator, the others remaining free. These constraining outputs are flux densities, current densities, slot fill factor, geometric constraints for instance.

FIRST OPTIMISATION : DESIGN AT HIGH SPEED

At this working point (full load at 6000rpm), the DC output current of the initial alternator is about 170 A, according to the model. The constraints of the design are : DC output current fixed to 170 A and size of the new alternator smaller than the initial one. Optimisation is performed and some trends are shown in Fig. 9.

Fig. 9.a : Efficiency

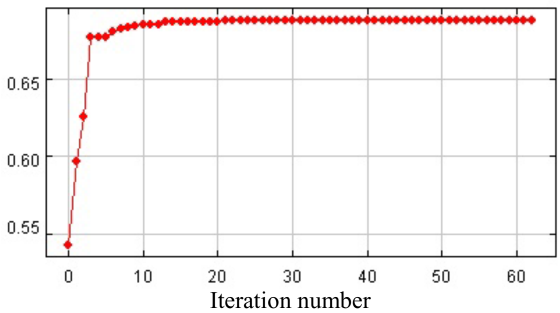

Fig. 9.b : Mass

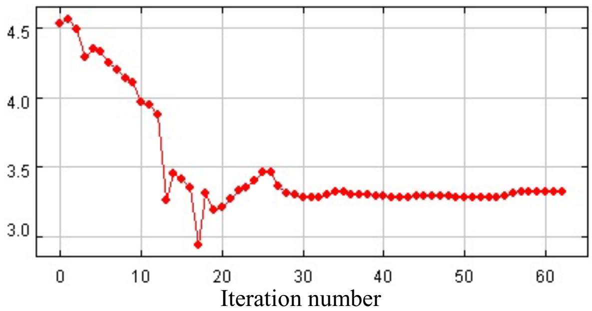

Fig. 9.c : Stator length

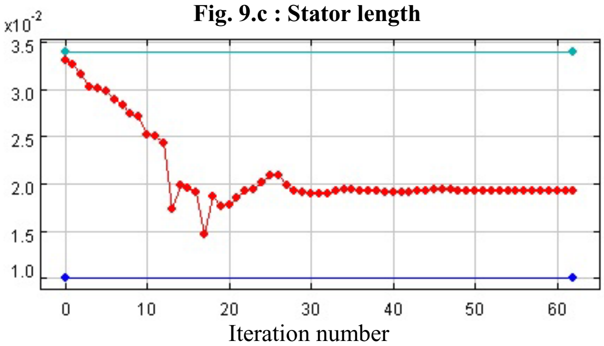

Fig. 9.d : Internal stator radius

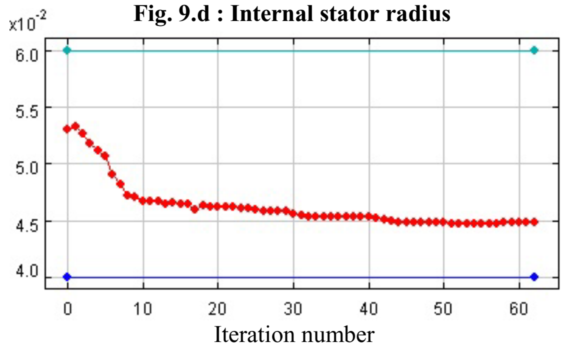

Fig. 9 : Parameters and characteristics evolution during optimisation for the first working point

Thanks to the optimisation process, efficiency increased from 54 % to 68 %, whereas mass decreased by 1 kg (Fig. 9.a and Fig. 9.b). The main sources of losses in a claw pole alternator are copper and iron ones. To reduce copper losses, the optimisation software limits the stator winding resistance. Therefore, the number of wire per slot is reduced and stator length squeezed (Fig. 9.c). As a consequence, the electromotive forces generated by the alternator are lower. However, power output could remain constant because the internal impedance, which is composed of stator winding resistance and leakage inductance, is lower. Another way to reduce stator winding resistance is to increase wire diameter. So, slot section could expand by decreasing internal stator radius, while external stator radius remains constant (Fig. 9.d). Thus, the wire section could also be increased until it reached the maximum achievable slot fill factor. Iron losses is therefore reduced in the new alternator design, because the magnetic flux density remains nearly unchanged, while mass decreases.

The alternator design given by the optimisation software seems to be very good for this particular working point. But if it is used at low speed, it could not work as well, because it has not enough electromotive force to get the same power output. That's why another optimisation must be launched for low speed.

SECOND OPTIMISATION : DESIGN AT LOW SPEED

The same optimisation is launched again with two differences : the working point is now "full load at 1300 rpm" and DC output current is set to 62 A according to the model. Characteristics evolution is shown in Fig.10.

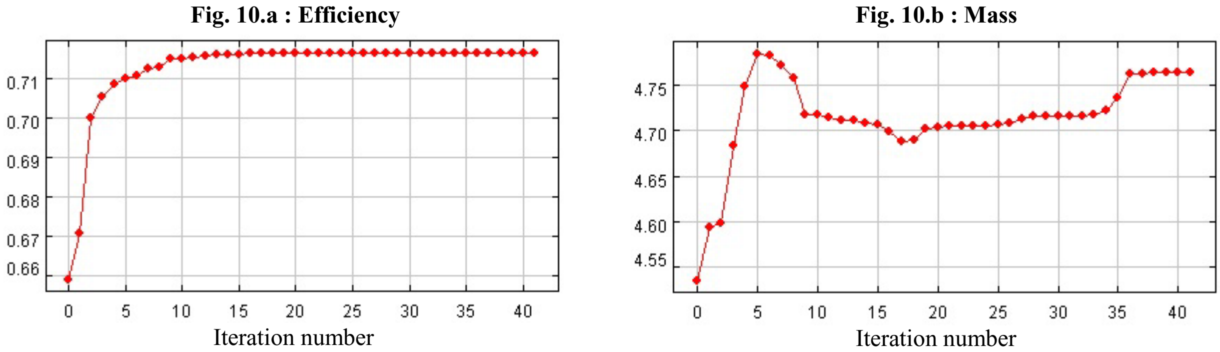

Fig.10 : Characteristics evolution during optimisation for the second working point

In this case, efficiency grows from 67 % to 72 % (Fig.10.a) while mass increases by about 0.2 kg (Fig.10.b). Efficiency gain is lower with this optimisation than in the previous one. At this working point, the optimisation software could not decrease the number of wire per slot, because the alternator needs enough electromotive forces to satisfy output current constraint. So, the only way to decrease cooper losses is to increase wire section. Like in the first optimisation, the internal stator radius decreases, while the external stator radius remains constant. Thus, the slot section is bigger and the wire area increases until the slot fill factor reaches its upper limit. The need for high electromotive forces implies that the magnetic flux remains nearly constant, so that the stator length can not decrease.

The optimisation process is very quick : it took only 3.7s for the first optimisation and 2.3s for the second one with a Pentium III, 1GHz. This reactivity allows designers to change design specifications at wish.

These two sizing show that alternator designs are different according to the considered working point. Future work will aim at producing an optimisation process, which will be performed taking simultaneously several working points into account. This should allow to design alternators suitable for a large range of speed and load.

CONCLUSION

The claw-pole alternator model presented in this paper is appropriate for electromagnetic design. It is based on magnetic equivalent circuit with analytical expressions of reluctances, linked with a first harmonic model of the electric circuit. The coupling with a sizing software, based on constrained optimisation, is quite simple. Thus, several sizing processes have been carried out, leading to an efficiency improvement for different working points. Even if these two sizing are not accurate enough, they show some trends that should be the same with a more accurate model. Future work will tend to increase simultaneously the efficiency of several working points. For example, several target working points will be simultaneously taken into account, in order to increase the system efficiency on urban cycles.

REFERENCES

[1]. G. Henneberger, R. Block, « Numerical calculation and simulation of a claw-pole alternator », Proceedings ICEM, 1992, pp. 127-131

[2]. G. Henneberger, S. Küppers, « Numerical procedures for the calculation and design of automotive alternators », IEEE Transactions on magnetics, vol. 33, no. 2, march 1997

[3]. M. Rakotovao, « Un modèle opérationnel complet pour l'alternateur à griffes dans le domaine automobile », Ph D thesis, Cachan, France, 1996

[4]. M. Hecquet, P. Brochet, « Time variation of forces in a synchronous machine using electric coupled network model » IEEE transactions on magnetics, vol. 34, no. 5, sept 1998

[5]. V. Ostovic, J. M. Miller, V. K. Garg, R. D. Schultz, S. H. Swales, « A magnetic equivalent circuit based performance computation of a Lundell alternator », IEEE transactions on industry applications, vol. 35, no. 4, july/august 1999

[6]. V. Caliskan, D. J. Perreault, T. M. Jahns, J. G. Kassakian, « Analysis of three-phase rectifiers with constant-voltage loads », IEEE, Power Electronics Specialists Conference, Vol. 2, 1999

[7]. F. Wurtz, J. Bigeon, C. Poirson « A Methodology and a Tool for the Computer Aided Design with constraints of Electrical Devices », IEEE Transactions on Magnetics, vol. 32, No 3, may 1996, pp. 1429-1432

[8]. E. Atienza, J. Bigeon, F. Wurtz, B. Belhabib, « Steps to an electrical design environment », IECON'99, Vol.2, pp. 815-820

[9]. Design Processing Technologies : www.designprocessing.com