Application of the VDA standard for the comparison and losses reduction of high efficiency car alternators

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Abstract--The reduction of the CO2 emission is a challenge for the future. Transportations are one of most important generator of CO2 and its reduction is directly linked to the reduction of the consumption of vehicles.
At the same time vehicles, for comfort and security systems, require more and more electric energy. The alternator efficiency has become of prime importance. Nevertheless, classic characterization of electric machines (maximum efficiency) is not sufficient for car alternators. We introduce the notion of the German VDA standard (Verband Der Automobilindustrie) which allows the comparison of different alternators and evaluate the relative share of the different losses.
A model is proposed and used for the determination of the VDA efficiency of a classic commercial car alternator. The relative share of the different losses is discussed and means of reduction are suggested.

Index Terms--Automotive alternator, efficiency, losses, modeling, VDA standard.

I. INTRODUCTION

To improve safety and comfort equipments in the automotive, power consumption of vehicles has grown steadily over three decades. Figure 1 illustrates this evolution since 1970.

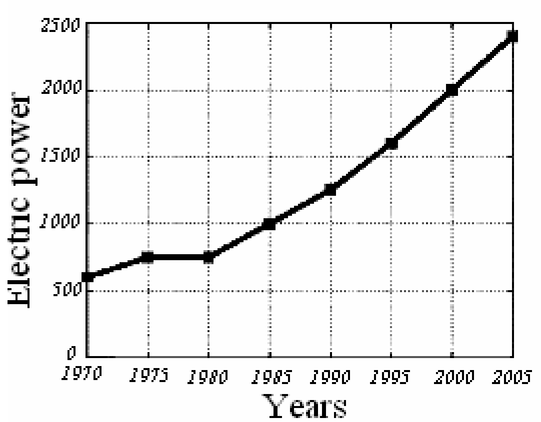

Fig. 1. Evolution of automotive power consumption (Watts) since 1970. [1]

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This increase added to a rise in oil prices and the arrival of anti-pollution standards more stringent leads us to an obligation of increase alternator's efficiency. In fact, claw-pole alternators structure exists for many years, but the improvement of its performances was not a priority, robustness and low cost of this machine made of it the reference in automotive electric generator.

In order to improve the efficiency of this alternator, studies were conducted to determine the losses of this machine. The representation of those losses is done using maps dependent on the speed of the machine and its excitation current. However, the main disadvantage of these maps is the difficulty of direct comparisons of different alternators. To remedy this problem a standard has been established to compare different alternators under the same operating conditions.

These conditions correspond to a cycle called ' VDA cycle'. The layout of these losses operation entails the development of a model of the alternator. In this article, we will present what the VDA standard is, then we will detail the various losses of the alternator and explain the choice of the model and the assumptions we made.
We will then analyze the results and the evolution of losses. This article must be seen as a possible model of an alternator with these specific cases, leading us to achieve representations of performance and separately losses.

II. THE VDA STANDARD

The mean of this standard is to be able to evaluate the performances of a generator in its operation area.

The VDA cycle is a standard which defines the operation of the generator at a rate equal to half the rated current that the alternator can be charged and for various values of speed: 1800, 3000, 6000, 10000 revolutions per minute. At each point, the alternator works for a period of time predefined by the standard that are 25%, 40%, 25%, 10%. The table Figure 2 represents the length of time of operation and speed matching.

Speed	Time period (%)
1800	25
3000	40
6000	25
10000	10

Fig. 2. Summary of the VDA cycle values.

Using this standard, we then calculate the various losses in the alternator as well as performance during the cycle.
The losses values during this cycle are performed for a given temperature.

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III. MODEL OF THE ALTERNATOR

Losses sources of an electrical machine are numerous. We will detail these losses in the case of a claw-pole alternator. This generator structure is based on the presence of an exciter coil in the rotor which allows an excitement order to obtain the desired output current, adapting to the rotor speed. Figures 3 and 4 illustrate this kind of alternator.

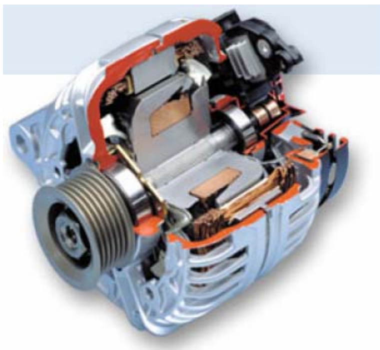

Fig. 3. claw-pole alternator.

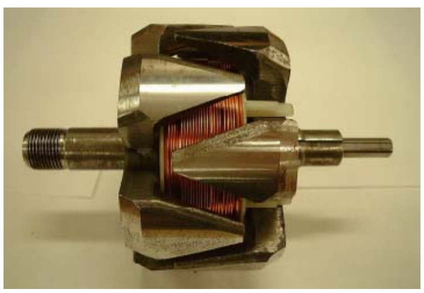

Fig. 4. Rotor of a claw-pole alternator.

The stator of a claw-pole machine consists of a three-phase winding, connected to a diode bridge.
All materials composing the alternator are the base of multiple losses. In the next part we will explain the model and the assumptions made during the modeling of each of those losses.

A. Determination of electromotive force

Claw pole alternator's geometry can leads us to consider this machine as a salient poles one. In fact, a Flux 3D simulation showed that for this kind of machine, Ld=Lq=Ls.
This simulation was conducted for an excitation current of 4A and gives as we said a salience ratio close to the unit (cf. Fig. 6).
As we considered this machine as a smooth pole one, we can model it thanks to the Behn-Eschenburg diagram as illustrated in figure 7, with a generator convention (cf. figure 5).

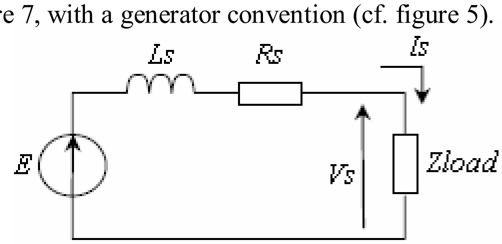

Fig. 5. Equivalent Behn-Eschenburg circuit for one phase of the alternator.

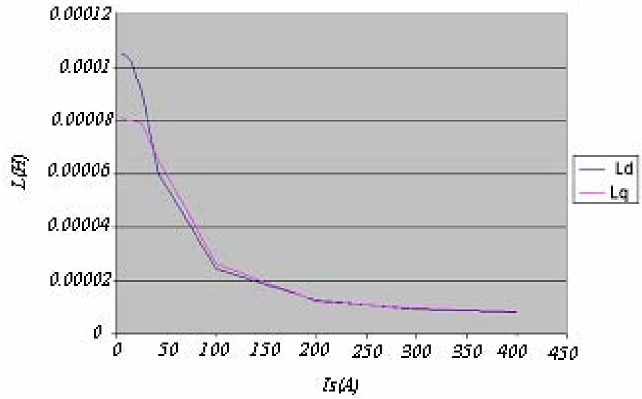

Fig. 6. Evolution inductors based on the output current of the machine. [2]

The purpose of Behn-Eschenburg diagram is to determine the magnetomotive resultant force E, from the current induces Is, the single-phase voltage winding Vs, parameters of the machine and assumptions made (smooth poles machine, no saturation, sinusoidal spatial distribution of flux density in the air gap).

Our model considers the alternator as a smooth poles machine, that is to say Xd=Xq=Xs.

$$\tilde{V}_s = \tilde{E} - R_s\tilde{I}_s - jX_s\tilde{I}_d - jX_s\tilde{I}_q \qquad (1)$$

With Vs, E, Is complex values, Rs and Xs correspond to the stator resistance and the reactance of the synchronous machine.

As the power electronics associated with the alternator is a diode bridge, the vector voltage Vs and the fundamental current vector Is are in phase, and knowing the parameters of the machine Rs and Xs, we can make our vector diagram to calculate E.

$$\tilde{V}_s = \tilde{E} - R_s\tilde{I}_s - jX_s * (\tilde{I}_d + \tilde{I}_q) \qquad (2)$$

The power equation can be written as:

$$\tilde{E} = \tilde{V}_s + jX_s\tilde{I}_s + R_s\tilde{I}_s \qquad (3)$$

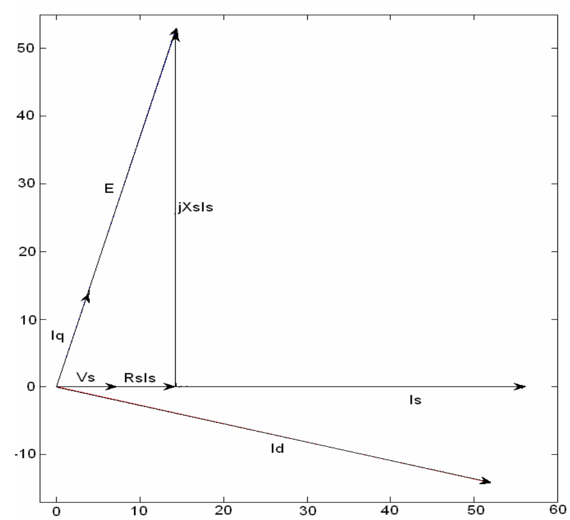

Fig. 7.Behn-Eschenburg diagram vector.

The vector diagram plot figure 7 is done for a constant temperature corresponding to a constant stator resistance.

The Vs_{eff} voltage is sinusoidal. In the case of a three-phase rectifier, this voltage can be expressed in the form:

$$V_{S\,eff} = \frac{\frac{\pi}{3} Us_{Moy}}{2\sqrt{2}\sin(\frac{\pi}{3})} \tag{4}$$

With Us_{Moy}, the average voltage output of the rectifier. The Is current determination is made for a given operating point considering the rectifier as perfect and the current constant.

$$Is = \left[\frac{P_{geneutil}}{3V_{S\,eff}\cos\varphi}\right] \tag{5}$$

With φ = 0 imposed by the rectifier.

B. Losses from the alternator

All of the losses can be represented in the Figure 8 form.

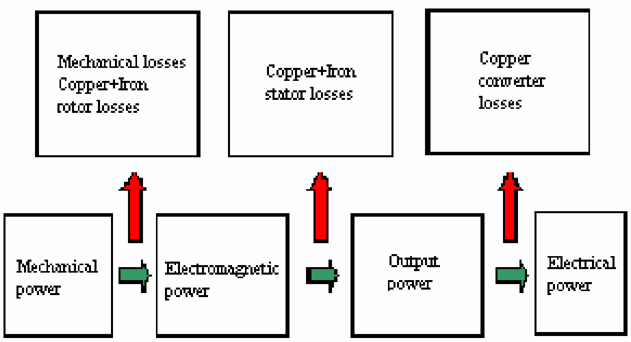

Fig. 8. Schematic losses. [2]

a. Rectifier losses

Before addressing the inherent losses of the machine, we can determine the rectifier losses. Diodes are not perfect components as shown figure 9, they have an intern Rd resistance. Copper losses are caused by this resistance and threshold voltage Vd.

To calculate the losses we assume that the characteristic of our diode is as follows.

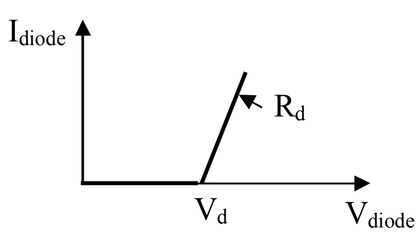

Fig. 9. Characteristic of a diode.

$$Vdiode = Vd + Rd * I_s \tag{6}$$

Our assumption for calculating the electromotive force in paragraph III.A was that the current phase in the stator is perfectly smoothed by the load. We assume that each phase is star coupled.

Each diode is throughput during the third period of sine wave. The energy dissipated in a diode during this time is the integral of elemental power:

$$p(t) = v(t)i(t) = [Vd + Rd.i(t)]i(t) \tag{7}$$

For a perfect DC current in the load

$$P = 2 * \left[(V_d * I_s) + R_d * I_s{}^2\right] \tag{8}$$

It is as if two diodes were all time conductive.

b. Copper losses stator / rotor

Copper losses in the stator are: $P_s = 3.R_s(\theta).I_{s\,eff}{}^2$ (9)

The rotor is only composed of one excitation winding so, copper losses (P_r) in the rotor are: $P_r = R_r(\theta).I_{ex}{}^2$ (10)

c. Rings / slip rings losses

The voltage drop between the rings and slip rings generate following losses: $P_{rs} = 2.V_{rs} I_{ex}$, (11)

where V_{rs} is the voltage drop between a ring and a slip ring.

d. Iron *losses*

Iron losses are composed of Eddy current losses and hysteresis losses.

Eddy currents losses results from the temporal variations of flux density which induce the electromotive forces. This E.M.F given birth to current which propagation is done in the alternator's iron.

Hysteresis losses result from a change of the material organization in field Weiss. This change is product by the variation in intensity and / or in direction of the applied flux density.

We will give details of the calculation of these losses to the stator and explain why this phenomenon is more complex in the rotor.

- *Stator iron losses*

To calculate these losses, we consider the value of the E.M.F determined by the vector diagram, and then we calculate the flux density in the air gap. This calculation involves the consideration of a sinusoidal flux density B in linear condition (without saturation). An alternator works frequently in flux weakening mode which help us to validate our assumption in an important part of the torque speed space. An analytical calculation, with the assumptions we made give the next flux density value in the air gap:

$$\hat{B} = \frac{Eeff\sqrt{2}}{pqN_1 Lfer \cdot D\Omega} \tag{12}$$

With p the pole pairs number, q the slot number by pole and phases, N_1 the coils number by slot, Lfer the iron stator length, D the outer stator diameter and Ω the rotor speeds in rad / s.

Once we have determined maximum induction with assumptions of non-saturation and sinusoidal flux density in the air gap, we can approach the iron losses depending on the Bertotti model.

Bertotti has used statistical tools to formulate precisely the different iron losses. This model is valid for a sinusoidal flux density.

$$P_{iron} = P_H + P_{EC} + P_E \tag{13}$$

$$P_{iron} = \underbrace{K_H f B_m^2}_{Hysteresis\ losses} + \underbrace{K_{EC}(fB_m)^2}_{Eddy\ current\ losses} + \underbrace{K_E(fB_m)^{\frac{3}{2}}}_{Exess\ losses} \tag{14}$$

The Bertotti coefficients K_H and K_{EC} are determined from the characteristic curves of steel plate. These curves represent the iron losses measured on an Epstein framework when the flow propagation is done in the lamination plate direction. Those losses are measured to an induction value of 1.5T for different frequencies.
So, for our application we see the limits of this iron losses calculating method. Indeed, the losses in Epstein framework are measured for a radial field and not for a transversal one. This model gives good results for 2D machines, these results become much worse for 3D machines as claw-pole alternators.

On the figure 10, with a 3D model, it appears that the flux density in the machine has an axial and radial component, that's why a Bertotti model of iron losses is given with the experimentation.
In order to know K_H and K_{EC} values, we will do a fitting of the curve. That is to say, knowing the losses curves we will determined the best K_H and K_{EC} coefficients in order to suit as well as possible the curve variation.
We consider two operation points of the machine and thus determine K_H and K_{EC} (excess losses are considered to be null).

$$operating\ \ frequency = \frac{speed(rpm) * p}{60} \tag{15}$$

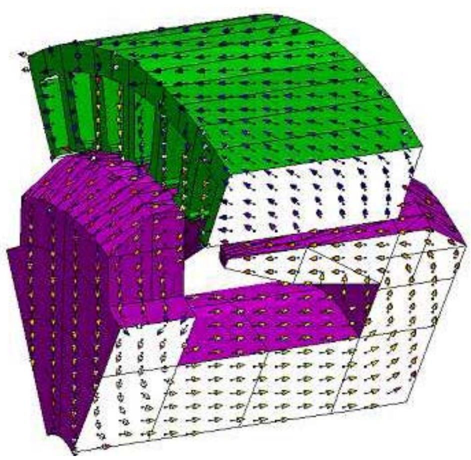

Fig. 10. Flux density in a claw pole alternator. [2]

- Iron rotor losses

The rotation of this part of the machine combined with the stator notching (reluctance variation of the air gap), leads to the emergence of eddy currents in the rotor claws. This part of the alternator is composed of a massive piece and so this process is increased. The magnetic induced reaction create, as in asynchronous machines, zig-zag flow causing the apparition of eddy currents in the skin thickness (δ = 2 * ρ / (μ* ω)).
Indeed, flux density lines being radial and transverse, eddy currents are free to spread in all directions of the material (see Figure 10).

The distribution of eddy current can be obtained in the simulation software Flux 3D with a defined time and speed pitch. Figure 11 illustrates the distribution of these eddy currents at a speed of 3000 rpm.

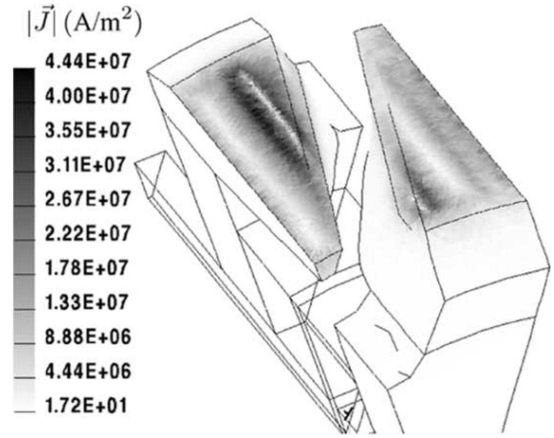

Fig. 11. Distribution of current densities on the surface of a claw. [3]

The variation of Eddy currents losses depending of the speed, for a given excitation current is shown Figure 12.

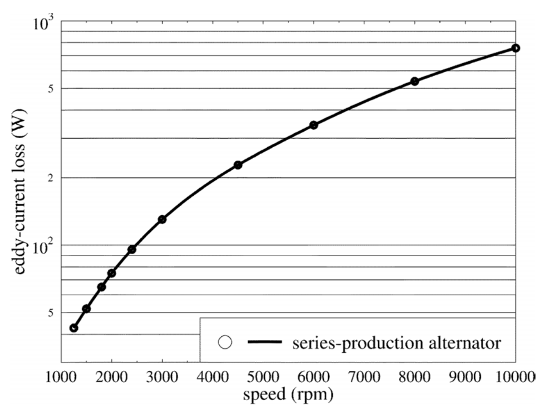

Fig. 12. Eddy current losses variations depending of speed. [3]

The model used to determine these Eddy currents losses is detailed by Henneberger and Kaehler [3] [4]. As calculation pitch has to be very small (to take into account the rotation phenomenon) and the mesh very fine, simplifications need to be done on the numerical method used.
The complexity of the phenomena encountered in the stator (due to its geometry), as well as the route to the stator flux requires a simplified 3D resolution. This simplification prevents us from having a precise characterization of these losses. Typically for a claw-pole alternator without inter-polar magnets, the proportion of iron rotor losses and stator ones is approximately 2:1 [5].

IV. RESULTS

We have previously presented and characterized the different losses of a generator. In this section we will analyze the results of this analytical modeling and those obtained by measurements. This comparison is carried out for an alternator Class 15 (outlet 150A at 6000 rpm).

A. Losses separation for the maximum output power

a. Simulation

This simulation is done with the analytical model presented before. As we explained, iron losses have been evaluated by a fitting of the real iron losses curve. This method allows us to obtained Bertotti coefficients on the global iron losses. Mechanical losses were obtained from measurements made at different speeds which enable us to achieve an interpolation of this curve. Those results are given figure 13.

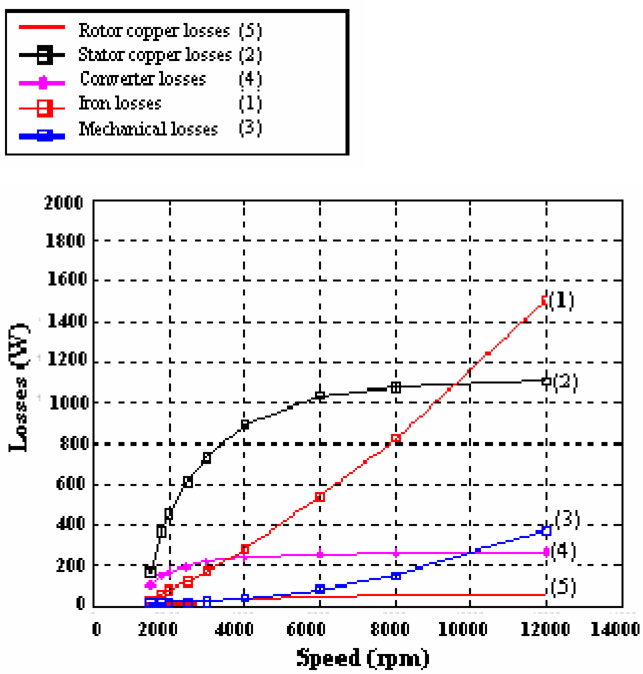

Fig. 13. Losses modeled. [6]

b. Experimental results

Figure 14 gives the experimental measures we have obtained.

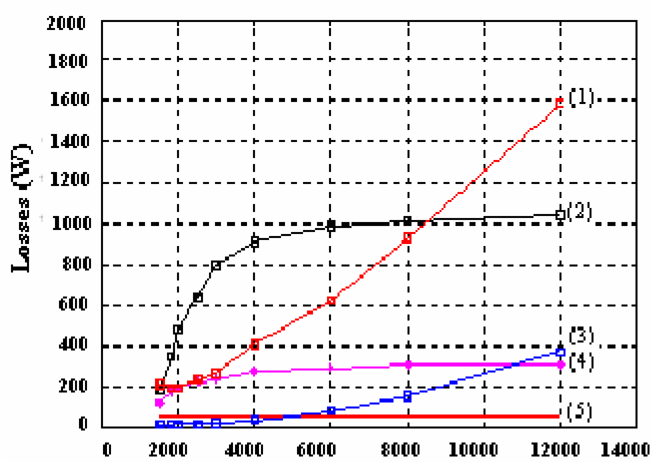

Fig. 14. Losses measured. [2]

d. Interpretation

Based on the assumptions and explanation of the phenomena observed, it is quiet clear that the Bertotti model would not work to represent the iron losses of a claw-pole generator. The curve of iron losses obtained by the modeling was calculated knowing the real losses curve of the alternator. With this curve, it was easy to determine the best Berttoti coefficients allowing us to suit best as possible measured losses. The graphs Figures 13 and 14 represent the evolution of separated losses in the machine depending on the speed for a maximum output power. We can observe that the modeling of the alternator from the cupper losses point of view, and the mechanical one is good. This conclusion is made since the results obtained by analytical approach match with those obtained by the measure.

Thanks to those curves we have a global vision of the different losses in the machine for maximum power and different speeds. In this condition it appears that iron losses seem to be very important.

The idea now is to have with this model, a mapping of losses depending on the power supplied by the alternator.

B. Map efficiency

This map is made knowing all the losses of the machine at different speed and for different values of the excitation current.

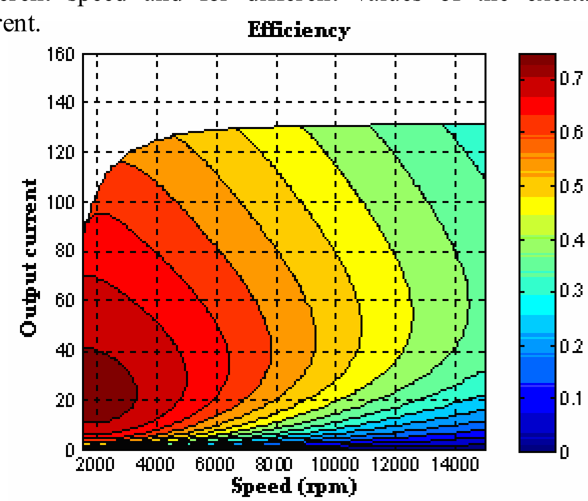

Fig. 15. Map efficiency at 20 ° C. [6]

The model we developed for the determination of efficiency allows us to know the efficiency of the machine for different operating points. But as we can see, there is a very wide variation of the performance in function of the operating point. That's why losses on alternators are measured by a standard, the VDA standard. The efficiencies values resulting of a simulation of the proposed model at 20°C, are shown in Figure 15.

C. The VDA standard

Losses during the VDA cycle are calculated for various speeds at the half of the current that the alternator can charge. Figure 16 illustrates the operating points during a VDA cycle.

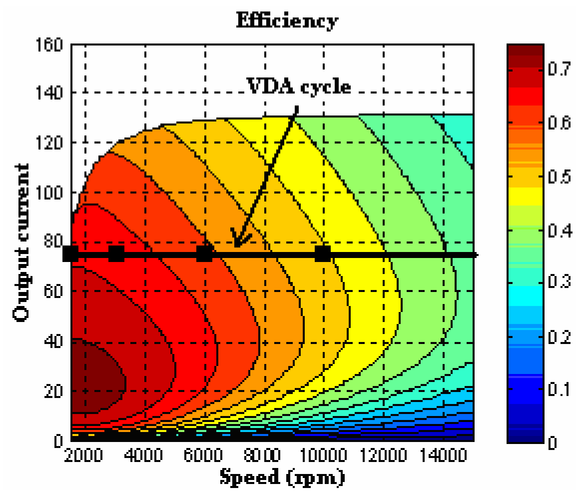

Fig. 16. Operating points in a VDA cycle. [6]

This standard had been introduced in order to have a better representation of the real efficiency of the alternator during his utilisation in a car. As we developed before, separation of iron losses is very difficult that is why we give a global representation of iron losses in the machine.

On the graph (Figure 17), we can see that with this representation, stator copper losses are most prevalent according to other losses, but also that stator iron losses are just as important as those in the rectifier.

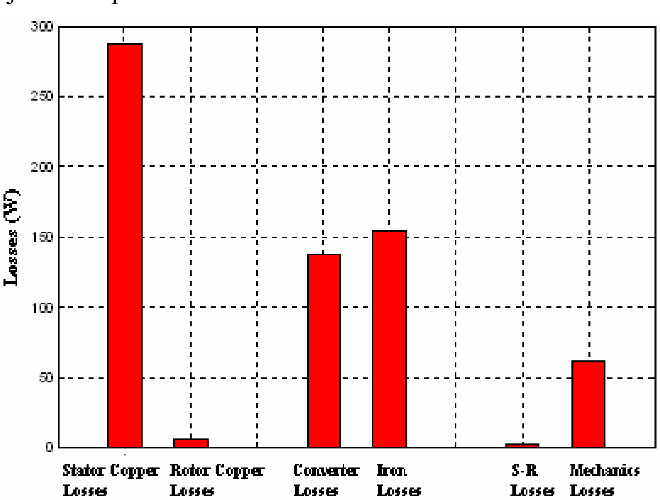

Fig. 17. VDA cycle at 20 ° C. [6]

With this losses representation, iron losses remain important but don't constitute the main part. They are of the same order than converter losses. Stator copper losses remain the main source of losses on the VDA standard.

This lost model of the alternator with these assumptions and therefore these limits from the accurately point of view, leads us to a characterization of this machine for all his operating points. The performance of the alternator on this VDA cycle at 20°C is 63.8%.

Figure 17 shows clearly the interest of the VDA standard. It is important to note the relatively large gap between the maximum efficiency (~75%) and the value of efficiency prepared in accordance with the VDA standard (~ 64%).

V. CONCLUSION

We have proposed in this article a modeling of automotive alternator with particular emphasis on the difficulty of determining iron losses. We have presented a model using experimental data allowing us to simulate mapping performance and involve maximum efficiency. However, this maximum efficiency is not real meaningful of the functioning of the alternator and we have therefore introduced the concept of VDA cycle to assess the relative importance of different losses in closer reality use.

In this context, it appears that the stator copper losses take an important part in global losses. These copper losses could be reduced by an increase in the winding coefficient, cutting heads reel or an increase in rotational speed of the alternator, which would reduced the number of stator coils.

The iron losses and rectifier losses appear at an equivalent level. These losses in the rectifier can be reduced by performing synchronous rectification (MOSFET). Iron losses can however be reduced by avoiding the three-dimensional field course and the induced currents in the rotor, that is to say by changing the structure of the machine.

Exploitation of these three areas will constitute the following of our study.

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