Improvement of an automotive alternator using the Experimental Design Method

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***Abstract*—This paper deals with the use of the Experimental Design Method for the study of electromechanical problems [1]. This methodology is here applied to the case of a wound rotor synchronous machine (WRSM) [2] - [3] used as a car generator. The Experimental Design method is a technique based on statistical concepts and aims at establishing the links existing between input variables (factors) and output ones (responses) [4] - [5]. Factors are typically dimensions and physical properties of the machine, while responses correspond to ”interesting” variables which are generally to be improved.**

I. Introduction

To improve the safety and comfort equipments in the automotive, power consumption of vehicles has grown steadily over three decades. Most of car alternators are based on a Lundell structure which allows low costs and high power density. Nevertheless, this structure presents relatively high iron losses due to a 3D magnetic flux path and high value induced current in the claws which reduces the efficiency for a high speed operation. From an other hand, it is difficult to increase the active length because centrifugal forces may deform the claws which can reach the stator for high speed operations.
In a previous paper [6], we try to separate different losses on this kind of machine and confirm that iron losses reaches high values and reduce the efficiency even in a VDA determination. To avoid this 3D magnetic flux we propose to study a ”classic” salient pole wound rotor synchronous machine (WRSM) which will be designed for a classic alternator car specification book. Due to high constraints, analytic models become inaccurate and so, classic optimization methods (for example SQP) become inadequate for this type of design.
We propose to use the ”experimental design method” where each ”experience” is issued from finite element model. The initial solution is deduced from an analytic model and a SQP optimizer. In other words, the SQP and experimental design method are used in a complementary way. For pedagogic reasons, only four design variables are investigated.
Firstly, this paper concentrates on the presentation of the (mainly graphical) tools outlining these inter variable connections, and secondly presents how these results can be used to deduce the operations to achieve, leading to efficient and sure improvements of the machine.

II. Machine design

This work is based on the geometry of a car alternator, which was initially defined thanks to a previous study. This part sum up the characteristics of the alternator (cf. Table I) and presents the factors chosen to be used in the experimental design analysis (Table II).

Name	**Description**	**Value**
Lfer	Iron length	110mm
Dext	Outside stator diameter	137mm
D	Inside stator diameter	99mm
NI	Ampères turns per pole	720
Jr	Maximum current density in rotor coils	$6A/mm^2$
Js	Maximum current density in stator coils	$20A/mm^2$

Table I
MAIN CHARACTERISTICS OF THE DESIGNED MACHINE

The geometry of the machine is shown in Figure 1.

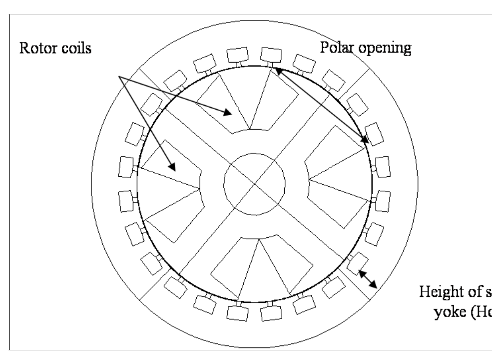

Figure 1. Design of the studied Wound Rotor Synchronous Machine

For the definition of the Experimental Design, four factors (input variables) have been considered:

- The polar opening coefficient (α)

- The height of the stator yoke (H_{cs})
- The height of the air gap (Ent)
- The number of the stator winding (Nsp)

Each factor is intended to vary between a lower and a higher bound. It is what we call a two level experimental design. It is quite clear that these limits cannot be fixed without a previous analytical study or without a good knowledge of the various electromagnetic phenomena involved. The table II sum up the mains characteristics of the generator:

Name	**Description**	**Lower bound (0)**	**Upper bound (1)**
α	Polar opening coefficient	0,7	0,85
H_{cs}	Height of the stator yoke	9mm	11,4mm
Ent	Height of the air gap	0,325mm	0,650mm
Nsp	Number of the turns of the stator winding	3	5

Table II
DEFINITION OF THE FACTORS VALUES

The following results are given for a rotor speed of 1800 rpm. However, for a complete car alternator study, this analysis must also be achieved for a speed equal to 6000 rpm. The corresponding results are not given here. All these simulations are made for a rotor excitation current of 5A. The following table gives the values we use for the design of the machine.

α	**H$_{cs}$**	**Ent**	**Nsp**	α	**H$_{cs}$**	**Ent**	**Nsp**
0	0	0	0	0,7	9	0,325	3
0	0	0	1	0,7	9	0,325	5
0	0	1	0	0,7	9	0,650	3
0	0	1	1	0,7	9	0,650	5
0	1	0	0	0,7	11,4	0,325	3
0	1	0	1	0,7	11,4	0,325	5
0	1	1	0	0,7	11,4	0,650	3
0	1	1	1	0,7	11,4	0,650	5
1	0	0	0	0,85	9	0,325	3
1	0	0	1	0,85	9	0,325	5
1	0	1	0	0,85	9	0,650	3
1	0	1	1	0,85	9	0,650	5
1	1	0	0	0,85	11,4	0,325	3
1	1	0	1	0,85	11,4	0,325	5
1	1	1	0	0,85	11,4	0,650	3
1	1	1	1	0,85	11,4	0,650	5

Table III
DEFINITION OF THE EXPERIMENTAL DESIGN

III. RESULTS-GRAPHICAL TOOLS

The Experimental Design Method gives the ability to establish the links existing between input variables (factors) and output ones (responses). In the frame of this work, we choose to study the output current as the unique response. In order to understand easilier the impact of the considered factors onto the response, it is useful to exploit graphical tools. Different types of graphical representations will be introduced in the article. The interpretation of the results given by this experimental design should then lead to effective improvements of the machine.

A. Finite Elements results

All the simulations made in this article, that is to say 2^4 simulations, are done with a Finite Element software (cf.Figure 3). The response observe is the value of the output current given by this experimentation (cf.Figure 2).

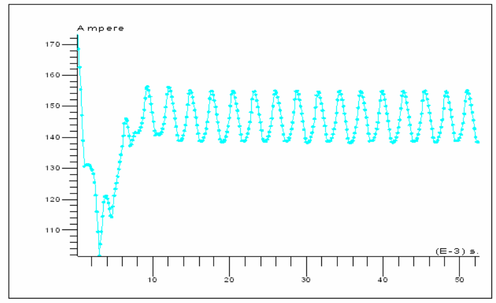

Figure 2. Rectifier output current

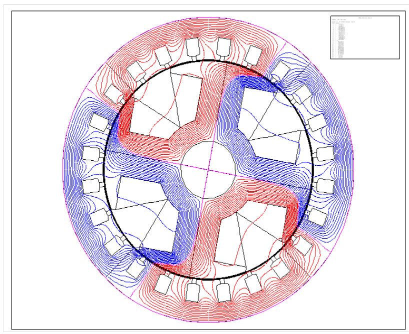

Figure 3. Magnetic flux path in the machine at 1800 rpm

B. Impact of each factor

A first kind of chart shows the impact of the variations of each factor on the response. This bar graph plots the effects of those input variable on the response, which variations are expressed with respect to the overall mean current values, obtained for each experiment of the design. Each effect is obtained by changing the factor from its medium value to its upper level. The variation of the current between these two values gives the gain induced by these changes. This graphical representation allows an easy comparison of each factor's impact (Figure 4).

This chart highlight the fact that at 1800rpm, the variation of the stator yoke height and the number of stator winding from his medium state to his upper one increase the output current. On the other hand, the variation to his lower bound of the polar opening coefficient and the air gap value, decrease the output current. Moreover, this kind of representation allows us to compare easily the impact of those variations. We can for example notice that the effect of the number of stator wound is more important than the effect of the stator yoke height ($E_{Hcs} < E_{Nsp}$).

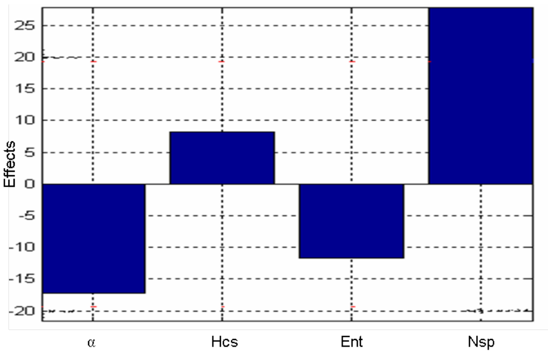

Figure 4. Histogram representation of each factor's impact

C. Impact of factor's coupling

A second kind of chart, Figure 5 represents the evolution of the output current, depending on the variation of two factors. It must be analysed as a square (4*4) matrix where rows and lines are constituted by the four variables.

For example, in the case circled in red on Figure 5, we observe:

- by the continuous line, the variation of the output current when the factor Ent takes its upper value, while the factor H_{cs} goes from its lower bound to its upper one (point 3 to point 4);
- by the dotted line, the variation of the output current when the factor Ent takes its lower bound and the factor H_{cs} goes from its lower bound to its upper one (point 1 to point 2).

The slopes of this curves may be interpreted as the level of influence of the considered variable. For example, if we look on the diagonal of the matrix (no interaction between variables), it appears that the variable Nsp is the most influent and improve the objective function (output current) for its high value.

If we are interested by the influence of two factors, it's quite clear that the most influent combination is with Nsp (line 4 row 1) Its contribution (the two factors at their high values) give an evolution of the output current from less than 80A to more than 150A.

The figure 6 gives an other vision of the same approach. This graph represents the effects on the output current compared with the average value. We can notice that the most influent (and performing) coupled factors is the combination of α and Nsp.

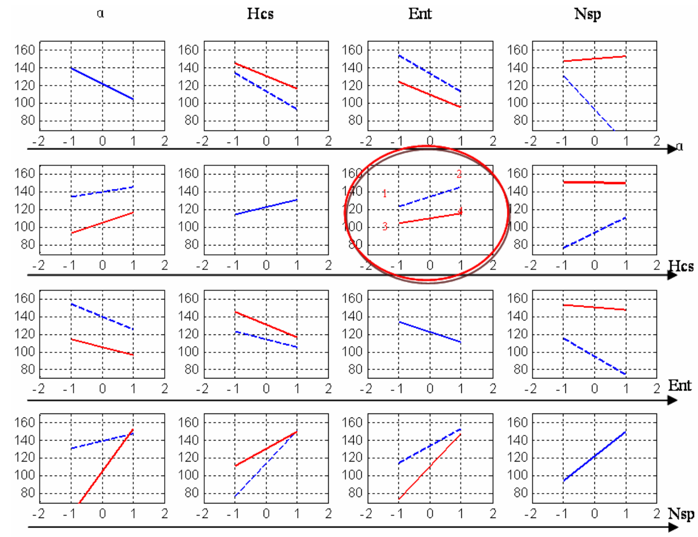

Figure 5. Matrix representation of two order interactions

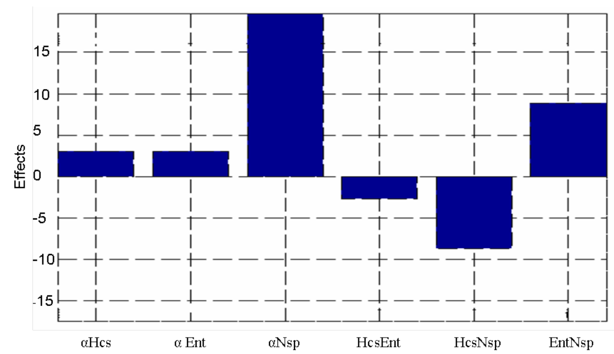

Figure 6. Histogram representation of two order interactions

D. Daniel's graph

This chart is also called "half normality plot" (Figure 7). On this figure, for readability reasons, the names of the different factors have been replaced by letters (see Table IV).

	Factor name	Description
a	α	Polar opening coefficient
b	H_{cs}	Height of the stator yoke
c	Ent	Height of the air gap
d	Nsp	Number of the turns of the stator winding

Table IV
DEFINITION OF THE INPUT VARIABLES

This kind of chart uses statistical considerations about the variations of the different factors. The y-axis uses a gaussian scale, that is to say based on a e^{-x^2} function. This kind of scale induces that gaussian like factors become aligned (red line in Figure 7). This representation is based on the assumption that noise variables evolve according to the normal variation law. This kind of approach constitutes a complementary method to the graphical representations presented before.

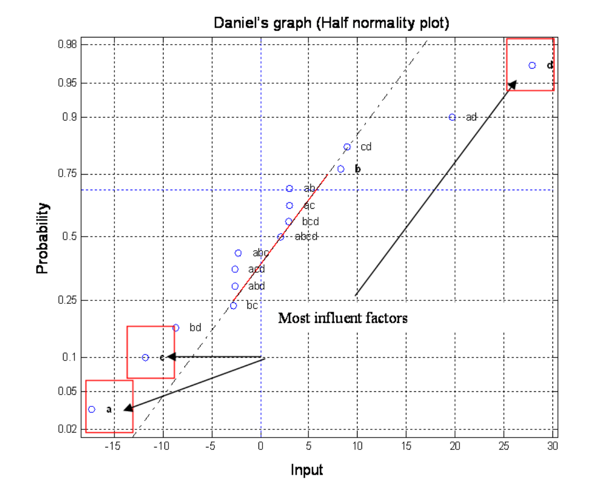

Figure 7. Daniel's graph

E. Optimization graph

Finally, we give a useful graphical tool, intended to represent the different steps to follow, so as to efficiently improve the machine (that is to say, increase the output current). This kind of representation is sometimes called ”Pareto graph”. It generally demonstrates the so-called ”80-20 rule”, that is to say that 80% of the possible improvements can be achieved by considering only 20% of the causes. In our situation, it is clearly the case. The variation of the Nsp factor (standing for of 1/4=25% of the number of factors) allows an improvement of 85,11%. For an optimal improvement process, the different factors have to be modified according to the instructions given by the optimization graph. Hence, considering the order (direction of the arrow in Figure 8):

- 1) the factor d (Nsp) must be increased (+) to its upper bound;
- 2) the factor c (Ent) must be decreased (-);
- 3) the factor a (α) increased (+);
- and finally 4) the factor b (Hcs) decreased (-).

For an optimum improvement of the output current we have to respect the order of the different optimization step. This order (1, then 2, then 3 (and 4)) allows an effective optimization (the growing of the output current). The increase of the d factor (Nsp) allows a gain of 27,8A (150,125-122,25=27,8A), that is to say an improvement of 85% of the maximum possible increase.
This graph gives then a global vision of the different optimization steps to follow.

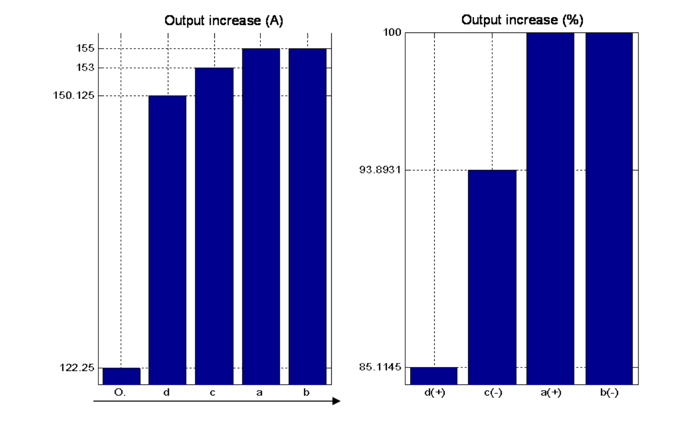

Figure 8. Optimization graph

IV. Conclusion

In this paper we have presented some methods for determining the influence of different input variables acting on a response, as well as the links between these factors. These tools are all based on the Experimental Design Method. This methodology can be applied in combination with various optimization methods (like SQP [2]), which are notably useful for finding initial conditions. We have then explained the interest of this kind of ”fast” improvement:
⇒ The time needed for this improvement (for our problem, it is five hours of simulation).
⇒ The possibility to select the influent coefficients only, in order to reduce the number of experiences.
This factor reduction may then allow the calculation of a second (finest) experimental design, in the vicinity of the optimum conditions found by the previous design.

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