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# DESIGN OF ELECTRICAL MACHINES AIDED BY FIELD CALCULATION AND FACTORIAL EXPERIMENTS METHOD

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## ABSTRACT

An approach for electrical machines design by using magnetic field computation coupled to factorial experiments is presented in this paper. Principles of factorial experiments are briefly reviewed and their application to design optimisation is explained. In this application experiments are replaced by magnetic field calculations. The procedure, which performs automatically all the numerical field calculations required, is described. The whole procedure is applied to a typical problem concerning permanent magnets synchronous motor with polar pieces.

## INTRODUCTION

Nowadays, magnetic field computation has become a compulsory tool in electrical machines studies. Magnetic field softwares are able to compute, in taking into account the saturation, several characteristics of a machine such as the flux or the torque waveforms, values of inductances or any other electromagnetical characteristics. Consequently, used in a particular environment, magnetic field computation provides a possible guide for electrical machine design in an attempt to optimize its dimensions with respect to the specifications.

To this aim, the introduction of magnetic field computation into a process of parameters variations and statistics processing, as factorials experiments, is proposed. Usually employed by industrials, the method of factorial experiments allows to know the behavior of a physical system with respect to a set of given factors. This knowledge is obtained by performing experiments [1]. In section one, we introduce the fundamental principles of factorial experiments adapted to the computation of the dimensions of an electrical machine by magnetic field software analysis.

In this application, simulations carried out by means of a magnetic field software analysis serve as experiments. Since there are many design factors a large amount of field calculations are required. For that, an automatic procedure for parameters variations driving the magnetic field computations

is necessary. Section two presents the method used to make an automatic link between the main design procedure and the magnetic field computation. This method frees the user from complicated task such as drawing or meshing.

Finally, as an example of the use of the whole procedure, we consider the problem of the evaluation of the influence of the following three parameters:

- air gap length;
- magnet width;
- slot opening.

on the rated torque and the torque ripples of a permanent magnet synchronous motor with polar pieces.

## FACTORIAL EXPERIMENTS

In a course of a design procedure, magnetic field computation code is very helpful to analyse the behavior and the performances of a projected machine. When a machine design must be optimised, a large amount of field calculations may be required. Factorial experiments are used here in order to planned these field calculations and to reduce their number. Optimisation of a machine design by factorials experiments associated with field computation is divided into three steps.

The starting point of the procedure is a preliminary design, obtained by analytical design equations and rules deduced from the theories of electrical machines and the designers own experience. At this stage the designer may estimate that some specifications are not matched by this preliminary design and desire to modify some factors in order to improve it.

At the first step of the procedure the designer must choose the main electromagnetical characteristics to be improved and the main influent design factors. In the terminology of factorial experiments method, the first type of variables are the output data and the second ones the input data. Let the output data be  $Y_1 \dots Y_k$  and the input data  $X_1 \dots X_n$ .

The second step consists of experimenting in order to know how the output data vary in function of the input data. Here experiments are replaced by magnetic field computations. From the set of magnetic field computation results the variations of

the electromagnetic characteristics ( $Y_k$ ) in function of the design factors ( $X_i$ ) can be modelled by polynomials. These polynomials can either be linear:

$$Y_k = \sum_{j=0}^n a_j^k X_j \quad (1)$$

or quadratic:

$$Y_k = a_0 + \sum_{j=1}^n a_j^k X_j + \sum_{i,j=1}^n a_{i,j}^k X_i X_j \quad (2)$$

The coefficients  $a_j^k$  or  $a_{ij}^k$  are obtained by applying the method of multilinear regression, based on the principle of least squares, on magnetic field computations results. The choice of the set of experiments or magnetic field computations corresponding with machine design factors must be very precise. With a study of  $k$  design factors on an electromagnetic characteristic, each of this factor having  $p$  levels of variations,  $p^k$  magnetic field computations must be carried out. Each of this computation is then characterized by a particular combination of values of the  $k$  factors. A matrix  $X$  is built with  $p^k$  lines and  $k$  columns: one line per magnetic field computation and one column per each coefficient  $a_i$  or  $a_{ij}$ . To reduce the size of the matrix  $X$  in keeping reliability and precision, several methods such as the fractional planes method or Taguchi method can be employed [2].

The matrix  $X$  is called the matrix experiments. Each line of  $X$  is composed of the value of the coefficient of  $a_j$  in relations (1) or (2) at each experiment. For instance if the modelling function is linear, the line  $i$  of  $X$  has the form:

$$1 \ X^i_1 \ X^i_2 \dots \ X^i_j \dots \ X^i_k \quad (3)$$

where  $X^i_j$  is the value of the factor  $j$  during experiment number  $i$ ,  $k$  is the number of coefficients  $a_j$  which is equal for the linear case to the number of influent factors,  $n$  is the number of experiments done. In the same manner an output matrix  $Y$  is built. The generic component of this matrix  $Y^i_j$  is the measure of output data number  $j$  during experiment  $i$ .

The coefficient  $a_j^k$  can be put in a matrix  $A$ . The generic coefficient of this matrix  $a_j^i$  is the coefficient relating the output  $Y_j$  to the input  $X_j$ . The matrix  $A$  is given by the relation:

$$[a] = [X^t \cdot X]^{-1} \cdot [X^t \cdot Y] \quad (4)$$

where  $X^t$  is the transpose matrix of  $X$ . The last step consists of optimising the machine design. For that purpose, the polynomials of

equations (1) and (2) are used with a method of optimisation such as the simplex algorithm or steepest-descent method.

### PROCEDURE FOR PARAMETERS VARIATION

To carry out the  $p^k$  electromagnetic computations, an automatic procedure for parameters variation is necessary [6].

To this aim, the notion of library of structures has been defined. A reference file including the data needed by the field calculation and an automatic data transfert module are associated to each structure of the library. A reference file is created only once for each structure of the library, from the preprocessor of the field computation software used. After choosing the reference structure, the data transfert module defines automatically the file for the field calculation. Reading the reference file, the procedure builds on the same structure the file of the studied machine by computing only some geometrical points. The geometry, areas, materials, winding and boundaries adapted to the new dimensions of the machine are included in this new file. This automatic procedure for parameters variation is simple and has been integrated in the method of factorial experiments. A little module which gives automatically the new dimensions data with respect to the chosen factors and their levels of variation of the studied machine has been developed. An overview of the whole procedure is shown on the figure 1.

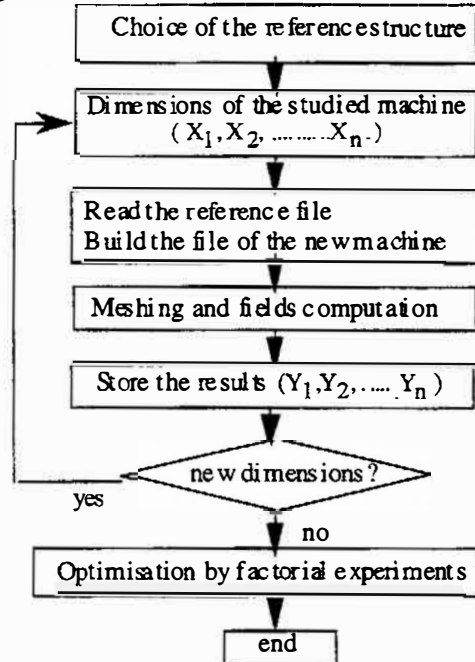


Fig. 1: Automatic procedure for parameters variations combined to factorial experiment method

## APPLICATIONS

This procedure is applied on a permanent magnet motor with polar pieces (Fig. 2). The aim of this study consists in the evaluation of the influence of the three following parameters:

- the width of magnet ( $X_1$ ),
- the slot opening ( $X_2$ ),
- the length of air gap ( $X_3$ );

on the values of rated torque and torque ripples.

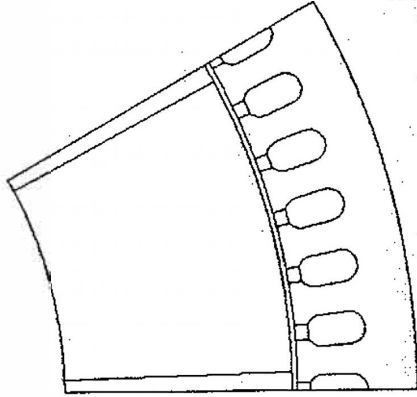


Fig. 2: One pole of the studied permanent magnet motor with polar pieces.

The motor to be optimised during this project is described by the following data :

|                    |                                      |
|--------------------|--------------------------------------|
| torque : 121.3Nm   | inner diameter of the stator:188 mm  |
| number of poles:12 | current density :8 A/mm <sup>2</sup> |
| number of slots:72 | torque ripples:16 %                  |

The experiments planning is based on the three factors  $X_1$ ,  $X_2$  and  $X_3$ , each of those factors having three levels of variation (Table I) and permits to obtain a model of the characteristics from a second degree quadratic polynomial as follows:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_{11}X_1^2 + a_{22}X_2^2 + a_{33}X_3^2 + a_{12}X_1X_2 + a_{13}X_1X_3 + a_{23}X_2X_3 \quad (5)$$

Polynomials are calculated by using the reduced values of these three factors: -1, 0, 1.

For the at load torque computation, a magnetic field software EFCAD based on finite elements method is used [3]. This software computes whole of the electromagnetical characteristics such as the torque, the inductances [4]. This software takes into account the movement of the rotor and the saturation of magnetic material [5]. Any system of supply currents is available. In

this study a supply by three phases AC currents has been considered. After magnetic field computations, the temporal evolution of the torque is analysed to obtain the average rated torque and the amplitudes of the torque ripples which are the output data.

Table II gives the values of output  $Y_1$  and  $Y_2$  obtained after the 27 magnetic field computations.

| variable   | $X_1$           | $X_2$        | $X_3$                            |
|------------|-----------------|--------------|----------------------------------|
| type       | width of magnet | slot opening | ratio air gap diameter / air gap |
| minimum -1 | 5,2510mm        | 45 %         | 225                              |
| center 0   | 5,5274mm        | 50 %         | 250                              |
| maximum +1 | 5,8037mm        | 55 %         | 275                              |

Table I : types and values of factors

|   | $Y_1$ | $Y_2$ |    | $Y_1$ | $Y_2$ |    | $Y_1$ | $Y_2$ |
|---|-------|-------|----|-------|-------|----|-------|-------|
| 1 | 119,8 | 14,9  | 10 | 121,6 | 13,9  | 19 | 123,6 | 14,4  |
| 2 | 120,6 | 15,7  | 11 | 122,0 | 14,8  | 20 | 123,9 | 15,7  |
| 3 | 121,1 | 16,4  | 12 | 122,2 | 15,8  | 21 | 123,9 | 17,0  |
| 4 | 119,0 | 16,9  | 13 | 121,0 | 16,0  | 22 | 123,5 | 16,5  |
| 5 | 119,6 | 17,5  | 14 | 121,3 | 16,4  | 23 | 123,6 | 16,7  |
| 6 | 119,9 | 17,9  | 15 | 121,3 | 16,5  | 24 | 123,6 | 17,2  |
| 7 | 118,2 | 19,2  | 16 | 120,0 | 18,2  | 25 | 123,4 | 18,8  |
| 8 | 118,5 | 20,0  | 17 | 120,5 | 18,8  | 26 | 123,3 | 18,8  |
| 9 | 118,6 | 20,5  | 18 | 120,4 | 19,1  | 27 | 123,3 | 19,1  |

$Y_1$  : rated torque (Nm)

$Y_2$  : torque ripples (%)

Table II magnetic fields computation results

After defining the experiments matrix, the coefficients of the quadratic polynomials which describe the answers  $Y_1$  and  $Y_2$  are calculated by relation (4).

For the rated torque  $Y_1$ , we obtain :

$$Y_1 = 121,32 + 2,0549X_1 - 0,6671X_2 + 0,2140X_3 + 0,3417X_1^2 - 0,0211X_2^2 - 0,1294X_3^2 + 0,3951X_1X_2 - 0,1945X_1X_3 - 0,1543X_2X_3 \quad (6)$$

And for the torque ripples, we obtain :

$$Y_2 = 16,35 - 0,279X_1 + 1,878X_2 + 0,587X_3 + 0,767X_1^2 + 0,432X_2^2 - 0,025X_3^2 - 0,267X_1X_2 - 0,016X_1X_3 - 0,299X_2X_3 \quad (7)$$

Figures 3 and 4 give an idea of the evolution of  $Y_1$  and  $Y_2$  in function of  $X_1$ ,  $X_2$  and  $X_3$ . Figure 3 shows the variation of the rated torque ( $Y_1$ ) versus the slot opening ( $X_2$ ) and the air gap ( $X_3$ ) when the magnet width ( $X_1$ ) is fixed. Figure 4 shows the variation of the torque ripples versus slot opening ( $X_2$ ) and magnet width ( $X_1$ ) when the air gap ( $X_3$ ) is fixed.

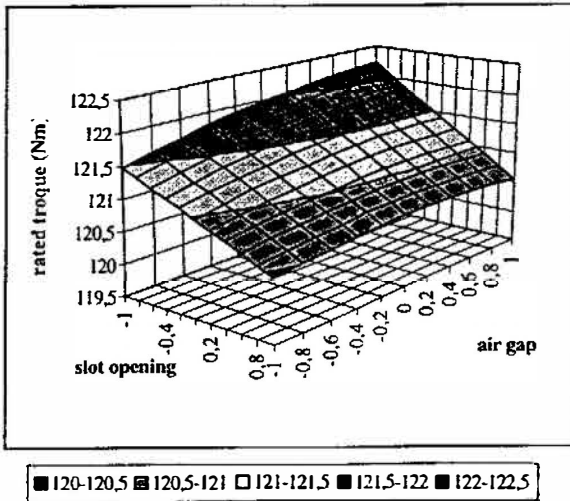


Fig 3: Isovalues of the rated torque when the magnetwidth is fixed

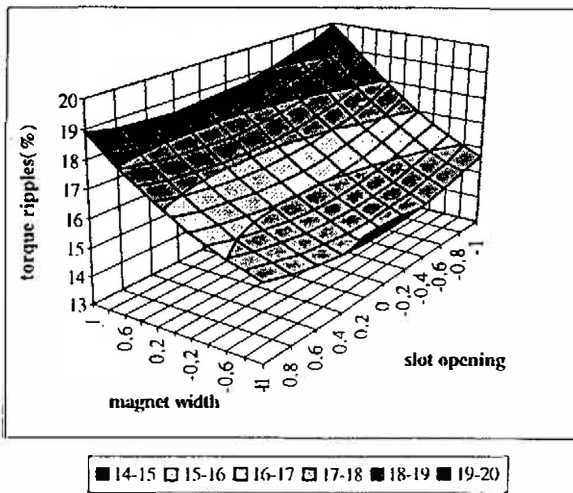


Fig 4: Isovalues of the torque ripple when the air gap is fixed

To verify the validity of the models, some results obtained by them are compared to those obtained from magnetic field analyses. These comparisons are reported on figure 5. For a better comparison, the values of the three factors  $X_1$ ,  $X_2$ ,  $X_3$  are not the same than those used for the building of experiment matrix X.

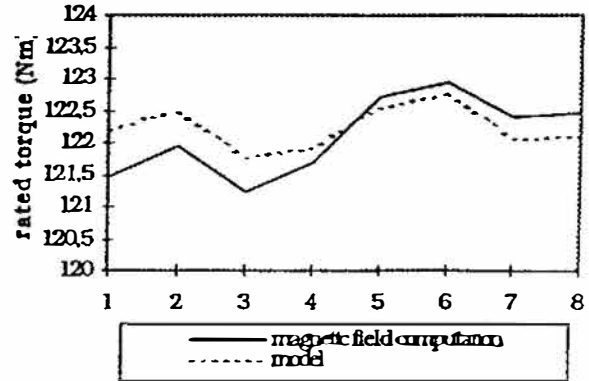


Fig 5 Comparison between the rated torque calculated by quadratic polynomial and the magnetic field computation

It can be noticed that the results obtained from the polynomial are in good agreements with those obtained from magnetic field computations. Good agreements between the results obtained from the two calculations are also obtained for the output  $Y_2$ . These comparisons show that the models are valid to predict the rated torque and the torque ripples for values of factors  $X_1$ ,  $X_2$ ,  $X_3$  corresponding to their variation intervals.

Once the validity of models is verified, several methods of optimisation can be applied to reach an optimum value of the chosen characteristics. In this paper the interesting point is fixed by a maximum rated torque or minimum torque ripples. The two polynomials which represent the evolution of the rated torque and the torque ripples are used to obtain the three values of  $X_1$ ,  $X_2$ ,  $X_3$ , according with the desired optimisation. The quasi-Newton algorithm has been applied to determine the results reported in the Table III hereafter.

|       | magnet<br>width<br>(mm) | slot<br>opening% | ratio air gap<br>diameter /<br>air gap | optimum<br>Nm |
|-------|-------------------------|------------------|--|---------------|
| $Y_1$ | 5,5267                  | 45               | 225                                    | 124,03        |
| $Y_2$ | 5,8037                  | 45               | 266,8                                  | 13,99%        |

**Table III : Optimisation results**

It can be noticed that the rated torque is slightly improved:

the preliminary design has a rated torque equal to 121.3 N.m and the optimised machine has a rated torque equal to 124.03 N.m. Same conclusions can be made for the torque ripples : the preliminary design gives torque ripples of about 16.4 % and the optimised machine 14 %.

### CONCLUSION

An approach to the problem of optimisation of electrical machine design by using a magnetic field computation code and the factorial experiments method has been developed and presented in this paper.

The treatment of magnetic field results by factorial experiments allows us to establish polynomials which link the design parameters to the electromagnetical characteristics. By means of those polynomials, it is possible to adjust the machine dimensions to match precise specifications.

Furthermore, once these polynomials have been calculated, it is no more necessary to use numerical code to compute electromagnetical characteristics in function of the design parameters. It's better to use these polynomials for that.

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