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On the Electromagnetic Stresses Impact on the Synchronous Generator Costs

In line with the nowadays requirements, the synchronous generators must fulfill the technical specifications and their costs should be as low as possible. For this, the electromagnetic stresses, which significantly influence the synchronous generator costs, must have optimal values. The use of optimal designs helps achieve this objective. In this work we show how the current layer A and the air gap magnetic displacement B_δ influence the generator's costs.

Keywords: optimal design, current layer, magnetic displacement

1. Introduction

Synchronous generators optimizations aims at establishing the structural dimensions, at choosing manufacturing materials, and parameter identification such that, for given technology and required operation conditions the final chosen design is the best of all possible variations [4]. Manufacturing know-how sustains the fact that the same synchronous generator with the same nominal data can be built in various ways with differ in structural design, dimensions, stationary and dynamic regime performances. The latter ones are influenced by the generator's electromagnetic stresses. In order to choose the optimal coefficient values for an optimal generator, the designer must compute several versions of the generator and select the one that fulfills the imposed requirements. These computations take a lot of time which can be shortened by the optimal designing programs.

2. Theoretical considerations in the optimization of a synchronous generator

The optimal design of synchronous generators starts by selecting the optimization criterion defined by a specific objective function. The optimal design is based on the mathematic design model [1]. The required objective function may aim at the generator's cost reduction, smaller structural dimensions, adequate operation in overstressing conditions, etc.

When the mathematical model is established, we select the main and local variables of interest for the optimal design, and we impose restrictions on these variables. The main variables in the synchronous generator designs are, mainly, electromagnetic stresses (air gap magnetic displacement B_δ, stator sider jug magnetic displacement B_{j1}, rotoric sider jug magnetic displacement B_{j2}, current layer A, stator winding current density J_1, operating winding current J_e, damper winding current density J_a). The local variables refer to generator's component sizes which vary during the whole design process depending on the main variables [5].

During program execution it is checked that the imposed requirements are respected. When all requirements are fulfilled the objective function parameter and coefficient values are displayed.

The main variables in the optimal design program being analyzed are: D (stator inner diameter), A, B_δ, δ (air gap), t_1 (dental tooth), J_1, β_{c1}, B_{j1}, B_{j2}, J_a, J_e, h_{02} (damper winding neck height), b_{02} (damper winding neck width):

The type of restrictions on a main variable generically named V_p are:

$$V_{p\min} \le V_p \le V_{p\max} \tag{1}$$

The optimization method used in the synchronous generator optimal design is the exhaustively exploration search method following the steps below [3], [4]:

- For each search direction given by the main and local variables fix the search step

$$\Delta V_p = \frac{V_{p\max} - V_{p\min}}{n_{V_p}} \tag{2}$$

where n_{V_p} is the number of intermediate search points in each direction, directions determined by the variables in the objective function;
- Begin the search starting from the minimum value of each variable;
- Compute the objective function for the set of variable values. The transition from a computation point to the next one is done by modifying the value of a single variable;

Computing the objective function for each set of variable values helps us find the global minimum of the function.

In this work we analyze the impact of the current layer A and of the air gap magnetic displacement B_δ on some of the synchronous generator optimization criteria. The most used criterion of design optimization is the economic one, defined by the total generator cost:

$$C_{t\min} = f(A, B_\delta) \tag{3}$$

This objective function has the following restriction:

$$C_{t\,\min} = C_{to} \le C_{tc} \quad (4)$$

In equation (4) C_{to} is the total cost of the optimally designed generator, while C_{tc} is the total cost of the classically designed generator. The generator's total cost is the manufacturing cost C_f and the exploitation cost C_e:

$$C_t = C_f + C_e \quad (5)$$

The manufacturing cost depends on the employed resources m_a (iron mass m_{Fe} and the copper mass m_{Cu}) and on their costs (iron cost c_{Fe} and copper cost c_{Cu}) as well as other administrative costs expressed by the k_r coefficient. In some applications $k_r = 8$, a value which we use in this work as well, without reducing its generality [5]. The exploitation cost depends on the sum of the synchronous generator losses Σp, on the normal operating life D_v, electricity costs c_{el},and the number of operating hours per year N_{ore}. The total cost is, therefore, expressed by the following equation:

$$C_t = \left(m_{Fe} \cdot c_{Fe} + m_{Cu} \cdot c_{Cu}\right) \cdot k_r + D_v \cdot N_{ore} \cdot c_{el} \cdot \Sigma p \quad (6)$$

3. An example application of the exhaustive search synchronous generator optimization

We apply the optimization steps described in Section 2 to a synchronous generator with the following nominal data: apparent output S_n = 350 kVA, rated speed n = 300 rot/min., rated voltage U_n = 400 V, and power factor $\cos\varphi$ =0.85. During the design we have taken that the generator is operating non-interruptedly, S1, its operating life being 15 years.

When computing the total cost we have used the following costs: c_{Fe} = 15 € – cost of a 1 Kg iron, c_{Cu} = 45 € – cost for 1 Kg copper, c_{ela} = 0,1 € – cost for 1 kWh energy, and c_{elr} = 0,03 € – cost for 1 kVARh quadergy.

The classical design has led to the following structural dimensions of the electromagnetic stresse: outer length L_e = 550.857 mm, stator outer diameter D_e = 1192 mm, current layer A = 324.311 A/cm, air gap magnetic displacement B_δ = 0.763 T, stator sider magnetic displacement B_{j1} = 1.397 T, rotoric sider magnetic displacement B_{j2} = 1.255 T, stator winding current density J_1 = 7.257 A/mm^2, operator winding current density J_e = 3.472 A/mm^2, damper winding current density J_a = 6.486 A/mm^2.

The main variables vary between -30% and 15% of the values obtained from the classical design [5]. Thus, the current layer range is A = (230÷370) A/cm and the air gap magnetic displacement range is B_δ = (0.53÷0.89) T. The optimal design program has given the following optimal values for the main variables: A_{oCt} = 369.66 A/cm, $B_{\delta oCt}$ = 0.759 T. This shows a 14% increase in the current layer and a decrease of 0.524% in the air gap magnetic displacement.

Using the optimal values of the parameters and quantities given by the optimization program, we plot various charts on which we can analyze the effects of optimization variables changes. In these charts we have marked with a yellow dot the classical design values and with a red dot the optimal design values. With green or blue dots we have marked the worst quantity values.

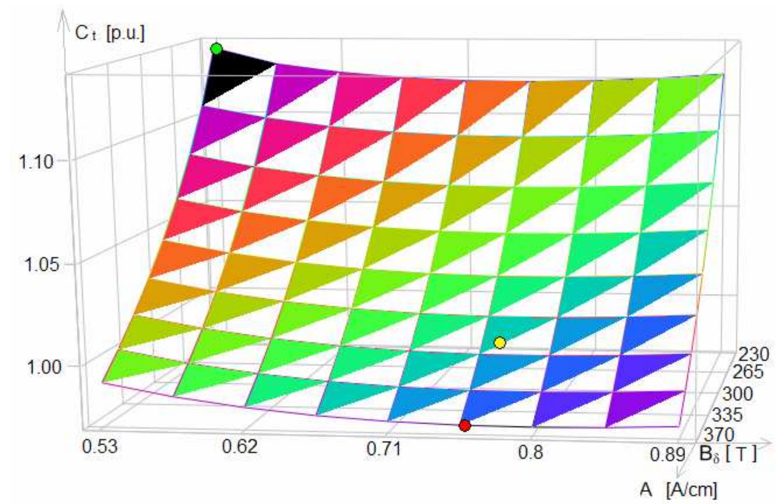

Figure 1. Total cost response surface

Figure 1 shows the response surface for the total cost. The optimal values for the current layer and for the air gap magnetic displacement show a 3.71% decrease in the total cost. The worst cost value, an increase of approximately 15% compared to the costs in the classically designed generator, is obtained when the current layer and the air gap magnetic displacement take the lowest values in the variation range, A = 230 A/cm and B_{δ}=0.53 T.

Since the total cost sums up the manufacturing and operating costs, we did an analysis of these quantities when taken as optimization criteria. Taking the manufacturing costs as the objective function and giving it as input to the design optimization program using the same main variables, we note that the lowest manufacturing cost for this generator (the red dot) is obtained when the current layer is A_{oCf} = 370 A/cm and the air gap magnetic displacement is $B_{\delta oCf}$ = 0.71 T (Figure 2). These values lead to a decrease of 8% in the manufacturing costs when compared to the classic design manufacturing costs. The highest manufacturing costs (the blue dot), with a 31% increase when compared to the classic design, is obtained when the current layer is 230 A/cm and the air gap magnetic displacement is 0.89 T.

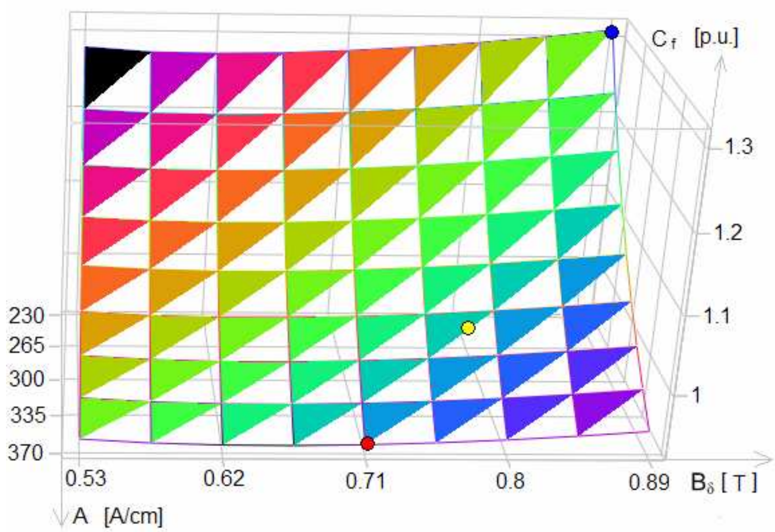

Figure 2. Manufacturing cost response surface

When interested in lowest operating energy losses, which mean lowest exploitation costs, we formulate this as an objective function, and, together with the two main variables (current layer and air gap magnetic displacement) we give it as input to the design optimization program.

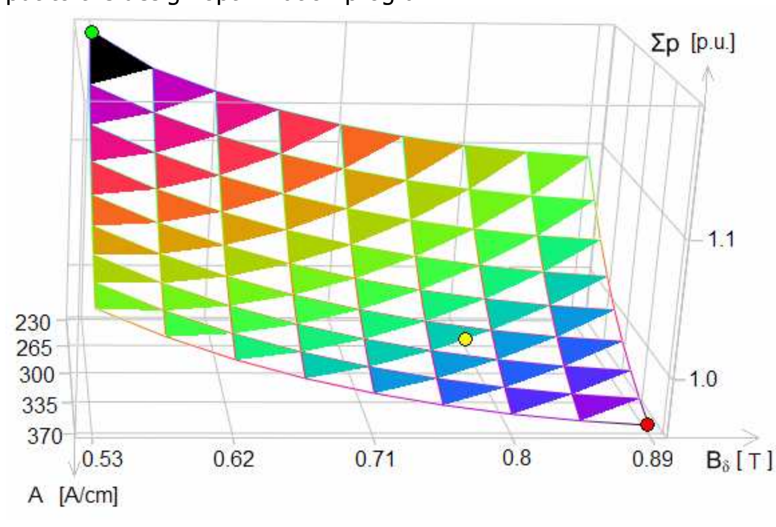

Figure 3. Total losses response surface

Figure 3 shows the losses response surface in the synchronous generator for the given variable restrictions. We note that the minimal losses are obtained for maximum values of the current layer and air gap magnetic displacement. There is a 5% decrease of total losses Σp compared to the losses following a classic design. Taking the minimum values of the main variables leads to a loss increase of 20%.

The way the total losses impact the exploitation costs is shown in Figure 4.

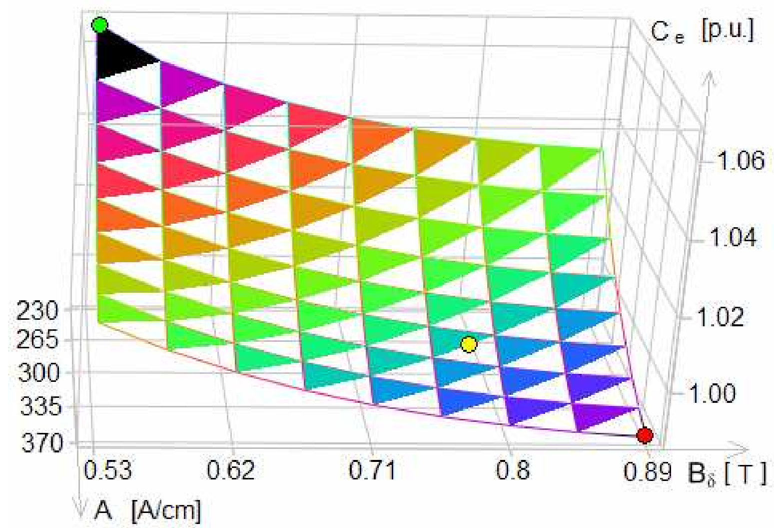

Figure 4. Exploitation costs response surface

Compared to the classic design values, the highest variables of interest values (A_{oCe} = 370 A/cm, $B_{\delta oCe}$ = 0.89 T) show a 2% decrease in the exploitation costs, while the lowest A_{oCe} and $B_{\delta oCe}$ values determine a 6.2% increase in exploitation costs.

4. Conclusion

The optimal design method we have applied for this generator type uses the minimum cost as the objective function. The main optimization variables are the current layer and the air gap magnetic displacement. This optimization set-up leads to a decrease of 3.7% of the total cost when compared to the total costs of a classically designed synchronous generator.

The chart analysis shows that requirements on the manufacturing, the exploitation and the total costs are fulfilled when the current layer takes the maximum value in the accepted range, A = 370 A/cm. This outcome is confirmed by the same experiment with the design of a synchronous generator having the same nominal data as in this work but with the rated speed being 1000 rot./min. In this case the total cost decrease was 3.4% compared to the total costs of a classically design generator [2].

The optimal air gap magnetic displacement values that fulfill the objective functions in this paper must vary in the upper half of the analyzed range B_{δ}=(0.53÷0.89) T, meaning that the air gap magnetic displacement should take values between 0.71 T and 0.89 T.

Knowing this, even when no access to an optimization program is possible, a designer can successfully specify a performant synchronous generator when choosing the electromagnetic losses values as recommended.

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