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Elisabeta Spunei, Ion Piroi, Florina Piroi

Optimizing Structural Dimensions and Costs of a Synchronous Generator Depending on the Current Blanket

Optimal structural dimensions and reduced costs are current requirements in electrical machines. Such requirements can be fulfilled already in the design phase by establishing optimal parameter and quantities values, such that the objective function is satisfied. The main optimization variable of this work is the current layer, the resulting optimal values and the charts analyzed here are obtained using a specific program for optimal design. This program is based on the classical design of the synchronous generator. Depending on the aimed objectives the program returns the values of the dimensions of interest. Using an optimal design, for the generator in question, costs have decreased with 4.7% compared to the classical design costs.

Keywords: *cost, optimal design, current blanket*

1. Introduction

The objective of optimizing a synchronous generator is establishing its dimensions as well as determining its parameter values in order to obtain a version that fulfills certain requirements. The mathematical models that are used in classical design are usually not leading to dimension and parameter values by which an optimal generator can be built. Using computers, electrical machines designers were able to create improved design algorithms and programs. Besides having the advantage of avoiding computation errors, such algorithms and programs have lead to significantly shorter design times.

The design presented in this work aims at finding the optimum values for the structural dimensions and optimal parameter values for a synchronous generator dependent on the current layer such that the total synchronous generator cost is minimal.

2. Theoretical Considerations in Optimal Designs of Synchronous Generators

Optimal design is done following the steps below [5]:

Formulate a mathematical model. The mathematic design model makes use of mathematical formulae found in the professional literature and in the manufacturing know-how. The model uses the material properties as well as their standard measured dimensions like, for example, magnetization curves for armature lamination, variation curves for various coefficients used in computations, standard conductor sizes, insulating materials types and sizes. The resulting mathematical model is utilized in the classical design without the iterations characteristic to the optimization process;

Choose the optimization criteria [1]. The optimization criteria may be technical, economical or functional. The technical criteria refer to technical operating performance. The economic criteria refer to the design of a generator such that its cost is lowest, during its whole running period. The functional criteria refer to generator designs that ensure a safe functioning during transient processes and short time emergency operations, without compromising the generator's integrity of the staff's health. In this work, the optimization criterion is the economic one;

Establish the objective function. The objective function is chosen depending on the optimization criterion. In this work, the chosen objective function is the minimum cost of the generator, minimum during its entire normalized functioning time. The objective function is defined as:

$$f\left(\bar{x}\right) = C_{t\min} = C_f + C_e \quad (1)$$

The *x* in equation ((1) is the optimization variable, C_t is the total cost, C_e is the exploitation cost, and C_f is the production cost. To this objective function we can impose various constraints. The constraint in this work is that $C_t < C_{tc}$, meaning that the total cost of the generator should be lower than the cost of an identical generator designed using the classical methods.

Establish the main optimization variables. Designs can be optimal in relation to one or more variables. The main variables, i.e. variables that predominantly influence the objective function and undergo value restrictions, can be: the current layer *A*; the air gap magnetic displacement B_δ ; the stator sider magnetic displacement B_{j1}, the rotoric sider magnetic displacement B_{j2}; stator winding current density J_1, operating winding current J_e; damper winding current density J_a; etc.

The main variables are subject to requirements provided in the professional literature. During the optimization process it is checked that the main variables comply with the imposed restrictions. In case a variable does not comply with such a restriction, it is given a new value and the computations are repeated until the main variable falls into the range accepted by the restriction. Since, in this work, the main variable is the current layer A, the objective function can be expressed as:

$$C_{t\min} = f\left(A\right) \tag{2}$$

In the professional literature, the current layer requirements for low tension, external poles generators are [2]:

$$A_{\min} \le A \le A_{\max} \tag{3}$$

that is:

$$200 \le A \le 500 \text{ [A/cm]} \tag{4}$$

Once the values of the main variables are fixed, we establish the value of the objective function for the generator being designed.

3. An Example Application of the Optimal Design Algorithm

We present here the results of a classical and optimal design of a three-phase synchronous generator with the following nominal data: apparent output S_n = 350 kVA, rated voltage U_n = 400 V, rated speed n = 300 rot/min., and the power factor cosφ =0.85.

For both design variants we have taken the non-interrupted operating life of the synchronous generator to be 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, c_{elr} = 0,03 € – cost for 1 kVARh quadergy [6].

The values of the main variables obtained using the classical design are: current layer A = 324,311 A/cm, the air gap magnetic displacement B_δ = 0,763 T, the stator sider magnetic displacement B_{j1} = 1,397 T, the rotoric sider magnetic displacement B_{j2} = 1,255 T, stator winding current density J_1 = 7,257 A/mm^2, operating winding current density J_e = 3,472 A/mm^2, damper winding current density J_a = 6,486 A/mm^2. Following these design values, the generator's structural dimensions are: exterior length L_e = 622,483 mm, the stator outer diameter D_e = 1188 mm.

The optimal design was done for variations of the current layer between -30% and 20% of the classical design current layer value. This led to the following optimal values for the main variables: A_o = 388,366 A/cm and B_{j2o} = 1,168 T. The rest of the variable had the same values as in the classical design.

This design has led to different structural dimensions for the synchronous generator. Therefore, the optimal structural dimensions are: exterior length L_{eo} = 550,857 mm, stator outer diameter D_{eo} = 1192 mm. One first observation is that the optimally designed generator's volume is now 89% of the classically designed generator.

Measures in the charts below are represented in the per-unit system (pu) according to the following generic relation, where the c subscript denotes values in the classic design:

$$x[u.rap.] = \frac{X}{X_c} \tag{5}$$

Figure 1 shows the variation curves of the outer diameter D_e and the outer length L_e , of the generator, depending on the current layer *A*.

The optimal design current layer value A_o = 388,366 A/cm led to an increase of 0.26% in the generator's outer diameter compared to the classical design, where *A* = 324,311 A/cm. At the same time with the slight increase in the outer diameter of the generator we notice a decrease of the external length with 9.38%. The negligible increase of the outer diameter is due to the fact the outer diameter is very little influenced by the value of the current layer. The generator's outer length takes into account the ideal length l_i, the number and width of the ventilation channels and of the axial length of the frontal caps. Thus, the decrease in the external length is due to ideal length which does depend on the current layer by the following relation [2], [3], [6]:

$$l_i = \frac{6 \cdot 10^{11} \cdot S_{iN}}{k_f \cdot k_B \cdot \alpha_i \cdot \pi^2 \cdot D^2 \cdot n \cdot A \cdot B_\delta} \tag{6}$$

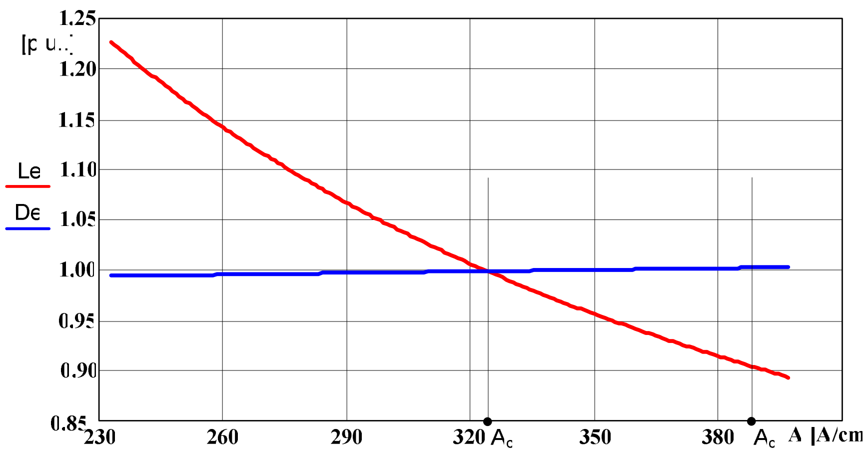

Figure 1. Variation curves of the structural dimensions depending on the current layer

The external length decrease is significant compared to the increase of the outer diameter implies that the iron mass will decrease significantly. We see this in Figure 2.

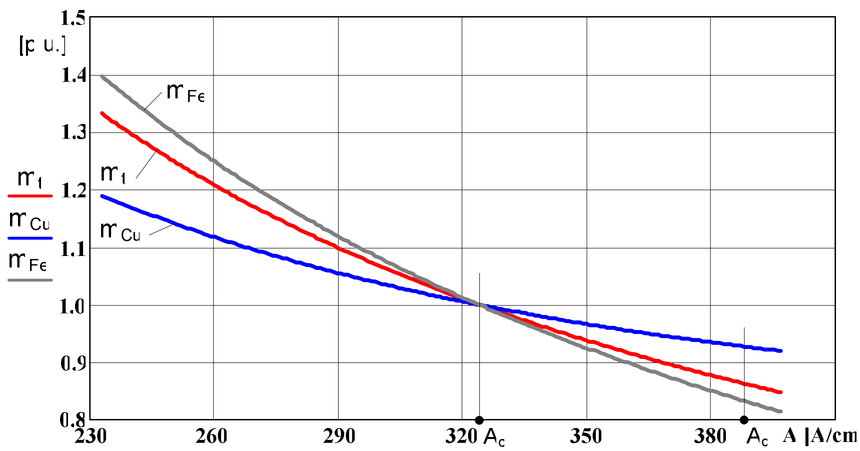

Figure 2. Mass variation curves depending on the current layer

The decrease of the copper mass can be explained by the fact that a shorter generator length leads to a shorter length of the copper conductor's active part and, thus, the copper mass needed by an optimally designed generator is smaller.

The total mass of a synchronous generator contains the active material masses m_a (iron and copper masses), as well as the connective materials, evidenced in the design program by the $k_M = 1{,}8 \cdot m_a$ coefficient [6].

The lower values of the active materials lead to lower losses (see Figure 3).

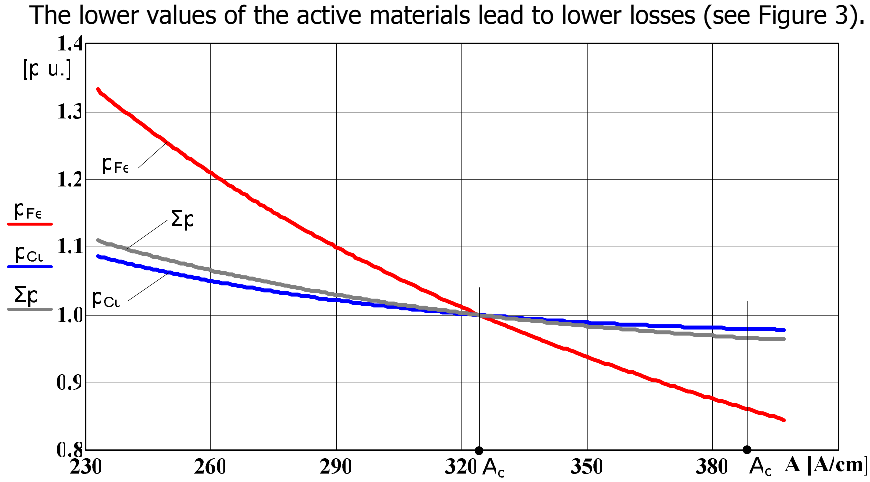

Figure 3. Loss variation curves depending on the current layer for a synchronous generator

The iron losses, p_{Fe}, contain the stator sider losses, the stator teeth losses, the rotoric sider losses, pole losses, and additional losses.

The stator and rotoric sider losses are in direct ration with the square of the outer diameter and the length of the stator's armature laminations, while the stator teeth losses and pole losses are directly proportional to the length of the statoric armature laminations. This leads to a 16.83% decrease of iron losses. At the same time the shorter length of the statoric windings lef to a 1.96% decrease of copper losses p_{Cu}.

The optimally designed synchronous generator's total losses Σp are with 3.28% lower than those of the classically designed generator. This decrease is not as big as the decrease in iron losses because it also contains the additional iron losses, the mechanical and ventilation losses. These losses are, in turn, influenced by the low decrease in the outer diameter, and, therefore, the decrease in the total losses is lower than the decrease in the iron losses.

The losses impact on an essential parameter of the generator. The optimally designed generator's efficiency increases with 0.31% (Figure 4). Although small, this increase is not to be neglected.

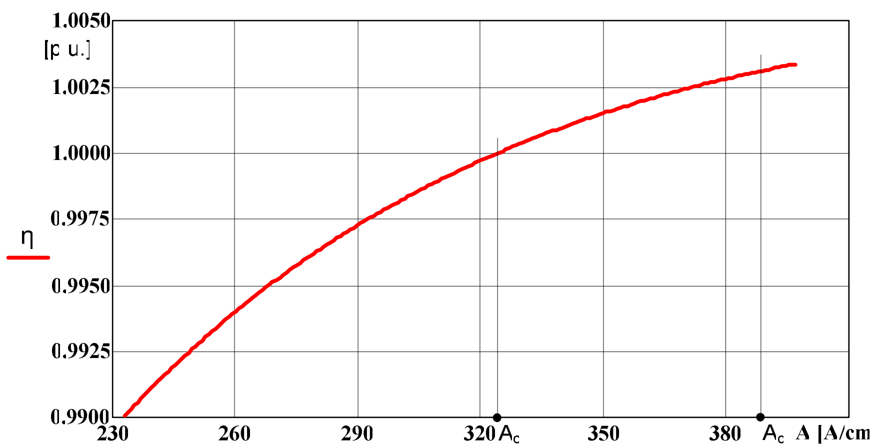

Figure 4. Efficiency variation curve depending on the current layer

During its non-interrupted operating life of the synchronous generator, the value of the losses significantly influences the exploitation costs. Figure 5 presents the cost variations of a synchronous generator depending on the current layer.

The exploitation cost C_e shows a 1.18% decrease compared to the costs in the classical designs. At the same time, the reduced mass of the synchronous generator leads to a 11.62% decrease of the manufacturing costs C_f , when compared to the manufacturing costs in the classically designed generators.

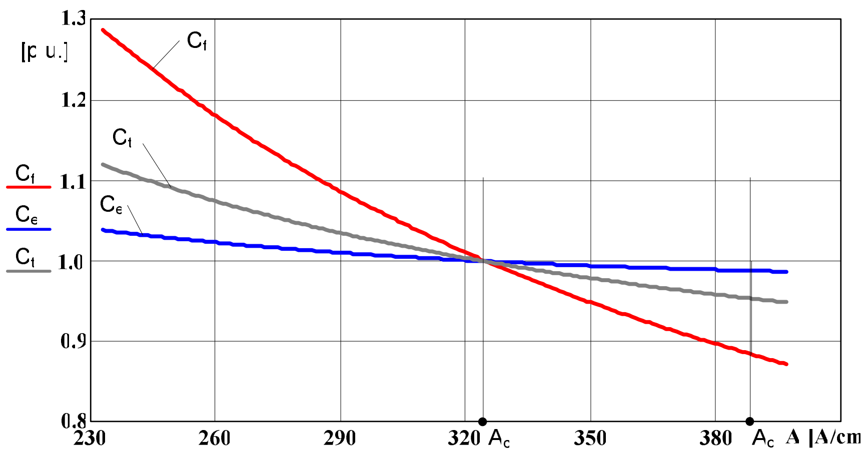

Figure 5. Cost variation curves depending on the current layer

In both designs, the manufacturing costs were calculated depending on the copper and iron costs needed in the manufacturing of the synchronous generator [6]:

$$C_f = 8 \cdot (C_{Cu} + C_{Fe}) \tag{7}$$

The total cost C_t shows a 4.7% decrease compared to the classically designed generator's costs. For a synchronous generator having the same nominal data but 1000 rot./min. speed, using the same optimal design we obtained a current layer optimal value of 486.65 A/cm compared to 424 A/cm in the classical design. This increase in the current layer leads to a 0.04% higher efficiency, to a 8.99% decrease of the manufacturing costs C_f, to a 0.8% exploitation costs C_e, and to a 3.4% decrease in the total cost [4].

4. Conclusion

The design of a synchronous generator using the optimization algorithm with the current layer *A* as a main variable did lead to a fulfillment of the objective function, that is, a lower cost.

Showing the results of an identical synchronous generator leads us to the following conclusions:

- To obtain a minimum cost of the generator, in the design conditions presented above, the higher value in the current layer should be chosen;
- Both the efficiency and the cost curves have a similar shape.

If the designer has no access to the optimization program, to obtain a performant generator, he/she should choose the higher value in the current layer.

The optimal program can be applied to any low tension synchronous generator. To design synchronous generators with a nominal tension higher than 1 kV (6÷14 kV) small adjustments are to be made when considering the insulations to be used.

References

[1] Gillich N., ş.a. *Cercetări operaţionale, Teorie şi aplicaţii* Editura Eftimie Murgu, Reşiţa, 2009.

[2] Cioc I., ş.a., *Maşini electrice. Indrumar de proiectare.* Vol. III, Editura Scrisul Românesc, Craiova 1985.

[3] Spunei E., Piroi I., *Maşini electrice. Proiectarea generatorului sincron,* Editura Eftimie Murgu, Reşiţa, 2011.

[4] Spunei E., ş.a., *Influenţa păturii de current din înfăşurarea trifazată a unui generator sincron, asupra costului total al acestuia,* Ştiinţă şi inginerie, Editura AGIR, vol 21, Bucureşti, 2012.

[5] Vlad I., ş.a. *Utilizarea metodelor numerice în proiectarea maşinilor electrice*, Editura SISTEC, Craiova, 2000, pg. 167-207.

[6] Vlad I., ş.a., *Proiectarea asistată a maşinilor asincrone – Probleme de optimizare,* Editura Universitaria Craiova, 2011.

Addresses:

- Lect. Drd. Ing. Spunei Elisabeta, "Eftimie Murgu" University of Reşiţa, Piaţa Traian Vuia, nr. 1-4, 320085, Reşiţa, e.spunei"uem.ro
- Prof. Dr. Ing. Ec. Piroi Ion, "Eftimie Murgu" University of Reşiţa, Piaţa Traian Vuia, nr. 1-4, 320085, Reşiţa, i.piroi@uem.ro
- Dr. Techn. Florina Piroi, "Eftimie Murgu" University of Reşiţa, Piaţa Traian Vuia, nr. 1-4, 320085, Reşiţa, florina.piroi@chello.at