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The Synchronous Generators Rated Speed's Influence on Electromagnetic Stresses and on Costs

During the design of synchronous generators is very important to establish the values of their electromagnetic stresses. The specific literature recommends that these stress values are to be chosen from the curves obtained during experimental design, where the independent values are the polar pitch and the number of pole pairs. The authors of this work propose a method of finding the dependency between the electromagnetic stress and the synchronous generator rated speed to rapidly estimate the stresses in a given interval of rated speed values.

Keywords*: synchronous generator, rated speed, electromagnetic stresses, optimal designing, total cost*

1. Introduction

The Romanian National Strategic Reference Frame establishes the intervention priorities of the Structural Instruments and makes the connection between the national and European development priorities. One of the CSNR's thematic priorities is increasing Romania's economic long time competitiveness [1].

At the European level, achieving this priority is backed by the European Operational Sectorial Program for Economic Competitiveness Growth which aims at increasing the efficiency in the Romanian industry sector [2].

In this spirit it is necessary to focus on a sustainable economic and social development, which directly depends on the strategic energetic sector. The said sector displays low performance due to the decaying infrastructure and low investments in producing electricity from renewable power sources.

Optimal design of hydro generators to equip hydro electrical appliances may partially but essentially solve problems in the electrical sector. Decreases in resource usage and energy consumption due to loss values are done already in the specific generator's design phase.

The total cost, C_t, of a generator is given by the manufacturing cost, C_f, and the exploitation cost, C_e, [3]. Computing the fabrication cost depends mostly on the active materials, m_a (copper, iron), and their price. The exploitation cost depends on the generator's losses, on the number of hours the generator works, and on the generator's operating life until the investment is recouped. According to the normal hydro generator's lifespan classification registry, a hydro generator's operating life is between 12 and 18 years [4]. For a hydro generator that functions autonomously, the annual operation time is 8640 hrs/year. To increase the energetic efficiency of a generator we need to know it's optimal total cost.

In this work we investigate the synchronous generator's rated speed on the electromagnetic stresses and their implication in the generator's costs.

We considered data gathered in the design of seven synchronous generators for micro hydroelectric power stations (MHPS) with a nominal efficiency of 300 kVA, a voltage of 400 V, a frequency of 50 Hz, a power factor of 0.85 and with the following rated speeds: 250 rpm., 200 rpm., 375 rpm., 500 rpm., 600 rpm., 750 rpm., 1000 rpm.

2. Optimal hydro generator design

The hydro generator's optimal design is based on the classical design equations which aim to fulfil a specific objective functions, where the optimization variables are chosen by the designer. The optimization variables are measurements that must fall within given intervals and influence the value of the objective function. In this work we examined the electromagnetic stresses ranges (power blanket A and the air gap electromagnetic induction, B_δ) for various rated speeds of the synchronous generator and their impact on the costs [5].

The optimal design is an iterative process, with loops and sub-loops, where each variable ranges over N_{it} values (N_{it} is 200 in this case). The values assigned to each variable range between -30% and 20% from the classic design values, $\overline{x}$, that is a variable ranges in the $(0,7 \cdot \overline{x} \div 1,2 \cdot \overline{x})$ interval. This interval can be modified as the designer needs, given that the requirements on the variables of interest are observed.

In this work we aim for the economic criterion to be fulfilled, an the objective function must, then, minimize the total cost, which is given by [6]:

$$f\left(\overline{x}\right) = C_t = C_f + C_e, \tag{1}$$

If at the end of iteration „j", the total cost C_{tj} is lower than the total cost, C_{tc}, obtained by the classical design, the lower value will replace C_{tc}. Otherwise we continue with the next iteration. The iterative design algorithm stops after N_{it} iterations and prints the values of the variables of interest for the designer for which the total generator cost is minimal.

We have implemented in MathCad the optimal design algorithm COMPLEX [7].

3. Optimal design results

In the design phase, the power blanket value, A, and of the air gap induction, B_δ, are estimated by plotting the values obtained by experimental design, depending on the pole pitch, τ, and on the number of pole pairs, p. After the hydro generator's fixed coil dimensions are established, we compute the exact values of the electromagnetic stresses, A and B_δ, and we verify that the restrictions imposed on them hold.

Choosing concrete values for A and B_δ, in the stresses' variation ranges depends on the design algorithm, on the designer's experience and on the bibliographic references used in the design. Thus, for a polar pitch in the (150÷700) mm range the power blanket value must fall in the (200÷520) A/cm range according to [8], in the (240÷510) A/cm range according to [9], in the (400÷640) A/cm range according to [10], in the (180÷510) A/cm range according to [11], and in the (200÷500) A/cm range according to [12]. For the same polar pitch range, the air gap electromagnetic induction must fall in the range (0,6÷0,94) T according to [8], in the (0,6÷0,915) T range according to [9], in the (0,65÷0,975) T range according to [10], in the (0,74÷0,89) T range according to [11], and in the (0,6÷0,9) T range according to [12]. Choosing any of these values influences, more or less beneficially, attaining the objective function. We deduce from there that in order to arrive at an optimal design we need to know the trends of the electromagnetic stresses values.

The rotating speed value directly impacts the electromagnetic stress values, since it depends on the number of pole pairs [12]:

$$f = p \cdot n, \tag{2}$$

where f is the frequency and n is the turation, and indirectly impacts the stress values by the polar pitch:

$$D = 100 \cdot \sqrt[3]{\frac{2 \cdot p}{\pi \cdot \lambda} \cdot \frac{60 \cdot S_{iN}}{n \cdot C}}, \tag{3}$$

$$\tau = \frac{\pi \cdot D}{2 \cdot p}, \tag{4}$$

In equation (3), λ is the pole's form factor, S_{iN} is the nominal internal power, C is the Esson constant, and D is the stator's internal diameter.

In the optimal design we tried to keep various coefficients constant as long as the restrictions on structural dimensions and other electromagnetic stresses (density currents in the stator winding, J_1, in the operating winding, J_e, in the dampening winding, J_a, the magnetic induction in the statoric sider, B_{j1}, in the teeth, B_d, in the pole body, B_m, in the rotoric sider, B_{j2}) are observed.

For the 300 kVA generator designed to operate at 250 rpm., the optimal current blanket value is with 19.834% higher than the value obtained using the classical design, while the air gap magnetic induction is with 12.799% higher as it can be seen in Figure 1.a). The red bullet marks the electromagnetic stresses values and the cost values obtained using a classic design. The green bullet marks the same values obtained using the optimal design.

These values lead to a 0.47% increase of the manufacturing costs, a 3.711% decrease in the operating costs, and a 3.186% decrease in the total cost.
When the same generator is designed to operate at 300 rpm., the electromagnetic stresses optimal values are with 19.831% higher for the current blanket and with 17.073% higher, for the air gap magnetic induction (Figure 1.b).

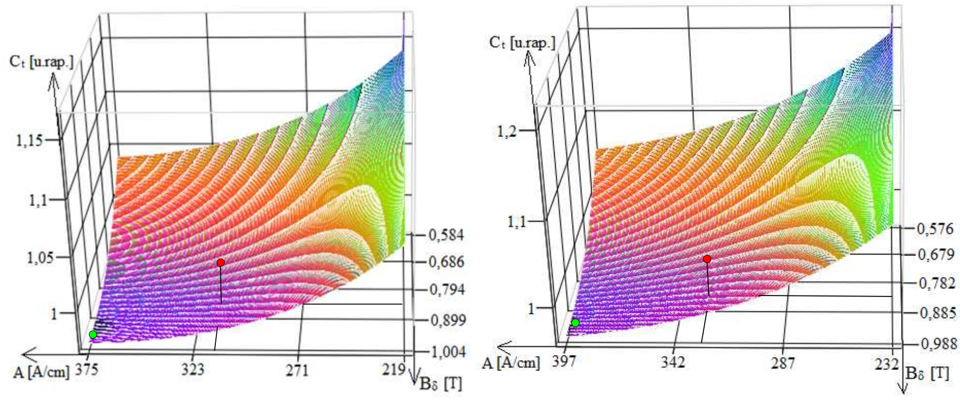
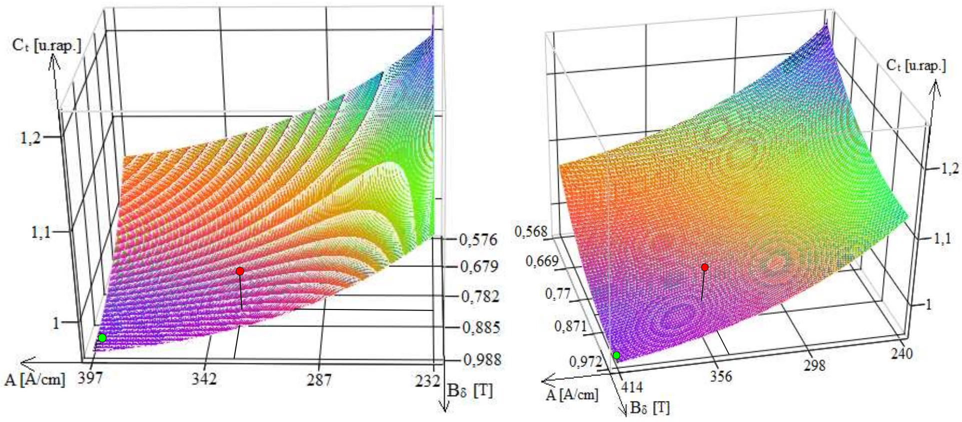


Figure 1. Cost variations depending on the current blanket and on the air gap magnetic induction for the: a) 250 rpm. and 300 rpm. generator.

These values lead to 1.436% decrease in the manufacturing costs, a 4.307% decrease of the operating cost and a decrease of 3.923% of the total costs compared to the costs obtained using a classic generator design.

For the generator operating at 375 rpm., the electromagnetic stresses optimal values are with 18.847% higher for the current blanket, and with 17.338% for the air gap magnetic induction. These values lead to a 2.918% increase in the manufacturing costs, a 3.694% increase of the operating cost and a 3.6% increase of the total cost (Figure 2.a).

For a generator designed to operate at 500 rpm. the electromagnetic stresses optimal values are with 19.843% higher for the current blanket, and with 19.088% higher for the air gap magnetic induction when compared to the values resulted using a classic design (Figure 2.b).

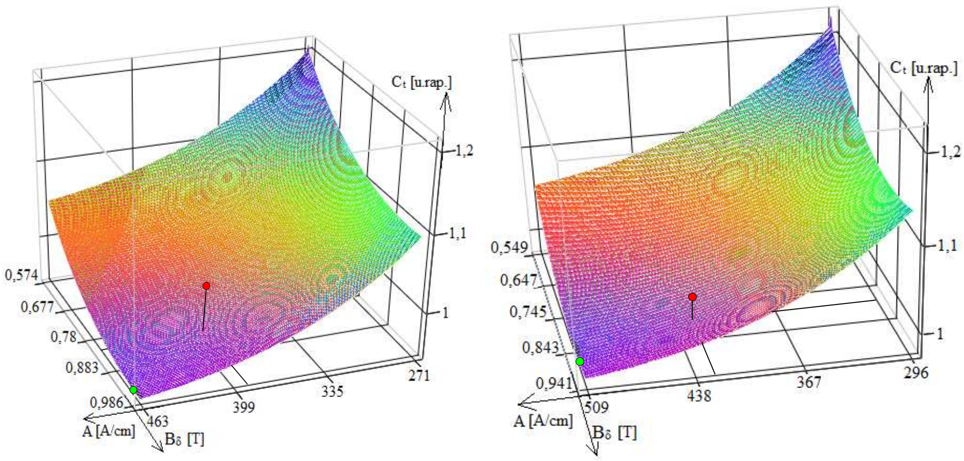


a) **b)**

Figure 2. Cost variations depending on the current blanket and on the air gap magnetic induction for the: a) 375 rpm. and 500 rpm. generator.

Also in this case, compared to the cost values obtain using a classic design, we obtain cost decreases as follows: 4.089% for the manufacturing costs, 4.291% for the operating costs, and 4.262% for the total cost.

Looking at the results of the classic and optimal design for a generator operating at 600 rot/min we determine a value 19.896% higher for the current blanket, and 19.776% higher for the air gap magnetic induction (Figure 3.a).



a) **b)**

Figure 3. Cost variations depending on the current blanket and on the air gap magnetic induction for the: a) 600 rpm. and 750 rpm. generator.

These values lead to a manufacturing cost decrease of 0.286%, of the operating cost of 6.063%, and of the total cost of 5.247%.

We look now at the generator that operates at 750 rot/min. Compared to the values obtained using a classic design, the optimal current blanket value is with 19,811% higher, while the air gap magnetic induction is with 8,684% higher.

These electromagnetic stresses optimal values lead to a manufacturing cost decrease of 2.286%, an operating cost decrease of 2.027%, and a total cost decrease of 2.063% (Figure 3.b).

Finally, for the generator designed to operate at 1000 rpm., the electromagnetic stresses optimal values are with 19.834% higher for the current blanket, and with 2.872% for the air gap magnetic induction.

These values also lead to decreases of the manufacturing costs of 1.499%, of the operating costs of 1.271%, and of the total costs of 1.3% compared to the values obtained using a classic generator design (Figure 4).

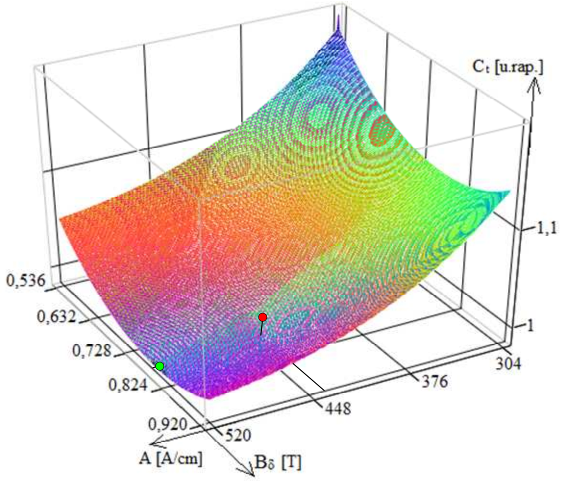


Figure 4. Cost variations depending on the current blanket and on the air gap magnetic induction for the 1000 rpm. generator.

Table 1

n [rot/min]	A [A/cm]		B_δ [T]	
	A_c	A_o	$B_{\delta c}$	$B_{\delta o}$
250	312,564	374,558	0,836	0,943
300	328,797	394	0,82	0,96
375	332	394,573	0,819	0,961
500	344,581	412,955	0,812	0,967
600	387	464	0,804	0,963
750	424	508	0,783	0,851
1000	433,569	519,563	0,766	0,788

Table 1 shows the optimal (index 'o') and classical (index 'c') design values for the electromagnetic stresses for the various generator rated speeds values.

Figures 5 show the same values in Table 1 in a graphical form.

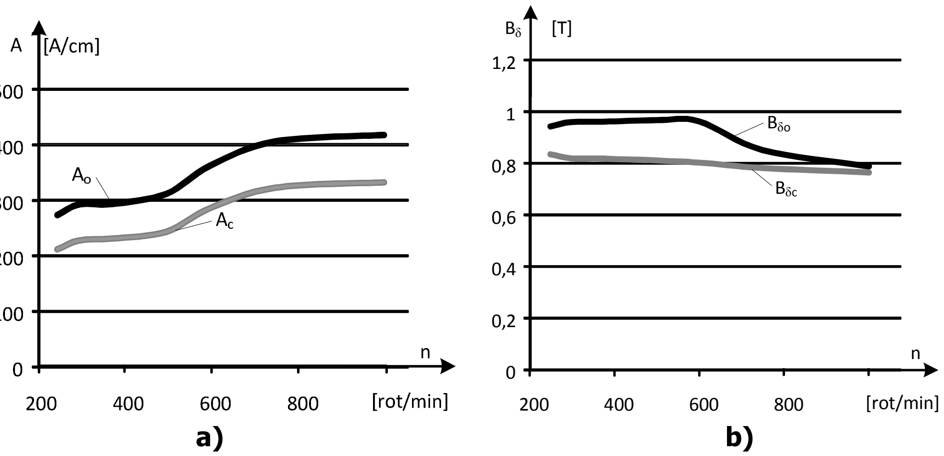


Figure 5. Current blanket and air gap magnetic induction variations depending on the generation's rated speed.

4. Conclusions

Keeping the synchronous generator' power constant, the power blanket increases as the rotation increases.

Keeping the synchronous generator' power constant, the air gap magnetic induction, B_δ, decreases as the generator's rotation increases.

The electromagnetic stresses values do fall in the value range recommended in the specific literature.

Fulfilling the objective function required by the optimal design results in electromagnetic stresses optimal values close to the upper limit of the accepted value ranges.

Knowledge of the electromagnetic stresses trajectory function of rotation and optimal choice of values for the stresses lead to technically efficient generators with reduced costs obtained by faster computations.

The optimal generator design results in higher values for the inspected variables, presenting wide variations for the current blanket in the 500÷750 rotation range, and wide variations for the air gap magnetic induction in the 580÷770 rotation range.

The values obtained by using the optimal generator design as well as its structural dimensions can be verified using the finite element method.

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