The influence of variation the inner diameter of the stator, $D$, upon the internal parameters, the costs and the efficiency synchronous generator

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Abstract: The designing of the synchronous generator assumes to determine the size of its component parts and internal parameters by which it must achieve the performances the required by the customer, thereby fulfilling a certain demanded criterion. In this paper, we propose to analyze the influence of the stator inner diameter variation, upon several internal parameters of the synchronous generator, upon the total cost, as well as it’s the efficiency. The analysis was carried after the conception of a program of optimal designing of a synchronous generator of 300 kVA, using MathCad software and comparing the results with those obtained by a pretty neat classical designing. These analyzes are intended to elaborate conclusions regarding the influence of the stator inner diameter values upon the analyzed parameters, in order to fulfill the objective function.

Key-Words: inner diameter, synchronous generator parameters, total cost, efficiency

1 Introduction
The designing of the synchronous generators, as well as that of all electrical machines have to meet certain objective functions the required by the beneficiary. The main required objective function is to obtain a lower total cost than that of the synchronous generator, obtaining the required technical performance [5].

If the required technical performance are more easily achieved (design based on nominal imposed data), to fulfill the objective function, the designer has to choose between more sizes, certain values, values that once were chosen, contribute to the achievement of the objective function either beneficently or unfavorably.

To determine the influence of different main variables chosen, upon other parameters, we designed a synchronous generator using two methods: the classical method and the optimal one.

In the optimal designing of the synchronous generator we have chosen as optimization criterion the economic criterion, and as objective function, a minimum total cost of the synchronous generator. Starting from these data and using MathCad software, we created a computer program through which we designed a synchronous generator destined to equip a small hydro. The nominal data of the designed and analyzed synchronous generator are: nominal power $S_n = 300$ kVA; nominal voltage $U_n = 400$ V; speed $n = 1000$ rot./min.; power factor $\cos \phi = 0.9$.

The present paper has as its object analyze the influence the inner diameter of the stator size, of the reactance value, short circuit currents, the total cost and efficiency of the synchronous generator. In this sense, using MathCad program and assigning to variable $D$ 200 values around from classical designing, we raised more graphs to be analyzed and we drew the afferent conclusions [4].

2 The analysis of the stator inner diameter influence $D$, upon the internal parameters
For determination the stator inner diameter value, $D$, the scientific literature indicates several methods, such as:

- using the curves resulting of the manufacturing experience;
- using the utilization coefficient, $C$, of the machine.

To determine stator inner diameter value, $D$, the curves resulting from the designing experience are based on $S_{IN}$, the interior apparent power, of the synchronous generator and $p$, the number of pole pairs. Using the value obtained, and depending on
the diameter coefficient, $k_D$, the external diameter, $D_e$, is determined the obtained value is normalized (if possible), to calculate later the final value of the inner diameter, using the relation [3]:

$$D = \frac{D_{\text{normalized}}}{k_D}$$

The determination of the stator inner diameter, $D$, by means of $C$, machine utilization coefficient, called the constant machine has as starting point the medium apparent tangential effort, $\sigma_s$, through which, it is indicated the requested electromechanical electrical machines, of a certain power. This coefficient is computed with the relation [1], [3]:

$$C = \pi^2 \cdot \sigma_s = \frac{S_{IN}}{n_1 \cdot I_1 \cdot D^2}$$

where $S_{IN}$ is the apparent inside power, $n_1$ is the synchronous speed, and $I_1$ is the ideal length of the generator. In the first stage of design, the value of this coefficient can not be calculated because there the dimensions of the generator are not known, that is the stator inner diameter value, $D$, and the ideal length, $I_1$, of the synchronous generator.

However, based on designing experience, curves were drawn through which one can determine the coefficient of the machine use, depending on the number of pole pairs, $p$, and the inside apparent power, $S_{IN}$. With the value of the utilization coefficient, determined from the graphs we can calculate the stator inner diameter, $D$, using the relation:

$$D = \sqrt{\frac{2 \cdot p \cdot 60 \cdot S_{IN}}{\pi \cdot \lambda \cdot n_1 \cdot C}}$$

where $\lambda$ is the pole form factor, determined from the graphs, depending on the number of pole pairs.

It follows that determining the optimal value of the stator inner diameter, $D$, is rather difficult, depending on more variables and consequently it is therefore necessary to know the main variables influence upon the internal parameters, the cost and the efficiency of the designed synchronous generator.

2.1 The influence of the stator inner diameter variation, $D$, upon the longitudinal reactance

The synchronous longitudinal reactance value, $x_d$, is influenced by magnetic air gap voltage-load, $U_{m\delta 0}$, which depends on the air gap, $\delta$, the polar step, $r$ and hence by the inner diameter value the of the stator, $D$, according to the relations [1], [2], [3]:

$$\delta = 0.4 \cdot \frac{\tau \cdot A}{B_\delta}$$

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

$$U_{m\delta 0} = 2 \cdot \frac{B_\delta}{k_E \cdot \mu_0} \cdot k_c \cdot \delta$$

$$x_d = x_{\sigma 1} + \frac{k_d \cdot \theta_1}{k' \cdot U_{m\delta 0}}$$

where $A$ is the current blanket, $B_\delta$ is in the air gap magnetic induction, $k_E$, $k_c$, $k_d$, $k'$ are the coefficients of the synchronous generator, $x_{\sigma 1}$ is leakage reactance per phase and $\theta_1$ is the solenoid armature reaction, that is the size equal to the algebraic sum of the conduction, electric current from the conductors that embrace a closed curve.

In Figure 1 we present the influence of the stator inner diameter variation, $D$, upon the longitudinal reactance of the synchronous generator. In the classic designing the value resulted for the inner diameter of the stator, is $D_g = 470$ [mm] and the resulted value in the optimal designing is $D = 609,6$ [mm].

Thus, at an increase of the value of the inner diameter of the stator with approximatively 30% (from the classic designing resulted value in (470 mm), to the value resulted from the optimal designing (609,6 mm)), the synchronous longitudinal reactance value $x_d$ increases almost proportionally, that is by 29,4%. Compared to the same reference values, the longitudinal transient reactance, has an increase of 7% and the longitudinal over-transient reactance, has an increase of 5,4 %. The longitudinal reactance values presented in the figure are in relative units, [ur].

The strong value increase of the longitudinal synchronous reactance is beneficial in limiting short circuit currents, both the permanent regime and the transient regime.
2.2 The influence of the stator inner diameter variation, \( D \), upon the transversal reactance

The value of the transversal synchronous reactance is dependent on the value of the inner diameter of the stator, \( D \), according to relations (1), (2), (3) and determined by the relation, [2], [3]:

\[
x_q = x_{q1} + k_q \cdot \theta_q \cdot (1 + k_c) 
\]

(8)

where \( k_q \) is the coefficient of the synchronous generator.

In Figure 2 we present the influence of the stator inner diameter variation, \( D \), upon the transversal synchronous reactance, \( x_q \), and transversal over-transient reactance, \( x_q'' \).

By analyzing the graph we found that the resulted value from the classic designing, when using the optimal designing, the transversal synchronous reactance value, \( x_q \), increases almost in proportion to the inner diameter of the stator value, \( D \), that is about 28.7% and transversal over-transient reactance value, increases with about 6%.

2.3 The influence of the stator inner diameter variation, \( D \), upon the inverse reactance and homopolar reactance

Because the reverse reactance value, \( x_2 \), is dependent on the longitudinal over-transient reactance, \( x''_d \) and the transversal over-transient reactance, \( x''_q \), according to relation (9), this is also dependent on the stator inner diameter value:

\[
x_2 = \frac{x''_d + x''_q}{2}
\]

(9)

If the synchronous generator supplies unbalanced loads, too, its performance is affected through the homopolar reactance, \( x_0 \), which also depends on the stator inner diameter value.

In Figure 3 we present the influence of the stator inner diameter variation, \( D \), on the inverse reactance, \( x_2 \), and homopolar reactance, \( x_0 \).

Compared to the inverse reactance value, \( x_2 \), resulting from the classical designing is found that the variation of the stator inner diameter, influences insignificantly this reaction, namely for the obtained value from the optimal designing, the increase is 0.75%.

The homopolar reactance is influenced more by the variation of the stator inner diameter, so for the resulting the value of the optimal designing is an increase with 8.13% towards the value resulting from classical designing. Reactance values are in relative units, [ur].

3 The analysis of the stator inner diameter variation, \( D \), upon the short circuit currents

In the synchronous generator operation can appear damage situations (short circuit) that can jeopardize its proper functioning. It is therefore very important to know the values of short circuit currents and the influence of various parameters, including of the stator inner diameter, on these currents.

3.1 The influence of the stator inner diameter variation, \( D \), upon the balanced three-phase short circuit currents

In case a balanced three-phase short circuit appears in the synchronous generator, the value of the winding currents increase, leading to the achievement of a maximum value, characterized by the over-transient short-circuit current value, \( I''_{d3} \), a smaller value, characterized by transient short-circuit current value, \( I'_{d3} \), and a much smaller value than the over-transient short-circuit current value, characterized by permanent short-circuit current value, \( I_{d3} \). These values are dependent on the longitudinal reactance.
values of over-transient, \( x'_d \), transient, \( x'_d \), and permanent regime, \( x_d \), according to the relations:

\[
I_{d3} = \frac{1}{x_d}; \quad I'_{d3} = \frac{1}{x'_d}; \quad I''_{d3} = \frac{1}{x''_d} \quad (10)
\]

It follows therefore that three phase the short circuit current values are influenced by the variation of the stator inner diameter. In Figure 4 we present the influence of variation of the stator inner diameter, \( D \), of these currents, which are represented in relative units [u.r.].

Following the analysis of the symmetrical three phase short circuit, it is found that, compared to the results of classical designing values, the permanently current value, \( I_{d3} \), decreases by about 21.9%, the current the value, \( I'_{d3} \), decreases by approximately 8.1%, and the over-transient current the value, \( I''_{d3} \), decreases by approximately 4.7%.

3.2 The influence of the stator inner diameter variation, \( D \), upon the over-transient biphasic and monophasic short circuit currents

When referring to monophasic or biphasic short circuit current, the values of the over-transient currents are higher than for three phase short circuit, because it intervenes reverse and homopolar reactance values, too, and the highest value of the currents is in over-transient regime and it can be calculated using the relations:

\[
I'_{d1} = \frac{3}{x_d + x_2 + x_0}; \quad I''_{d2} = \frac{\sqrt{3}}{x''_d + x_2} \quad (11)
\]

where \( I'_{d1} \) is the over-transient monophasic short circuit current, and \( I''_{d2} \) is the over-transient biphasic short circuit current.

In Figure 5 we present the influence of variation of the stator inner diameter, \( D \), the over-transient biphasic, monophasic short circuit currents, are represented in relative units [u.r.].

Following the analysis of the symmetrical three phase short circuit, it is found that, compared to the results of classical designing values, the permanently current value, \( I_{d3} \), decreases by about 21.9%, the current the value, \( I'_{d3} \), decreases by approximately 8.1%, and the over-transient current the value, \( I''_{d3} \), decreases by approximately 4.7%.

Towards the values resulting from designing classical, is found a decrease with 8.1% the over-transient monophasic short circuit current and a decrease with 3.3% the over-transient biphasic short circuit current.

4 The analysis of the variation of the stator inner diameter, \( D \), upon the costs of the synchronous generator

Logically, the synchronous generator size must influence the total cost, \( C_t \), the latter using the active materials costs, which are included in manufacturing cost, \( C_m \), and the losses in these materials, which are included in operating costs, \( C_e \) defined throughout the normated life cycle of the synchronous generator. To determine the cost of active materials and thus the manufacturing cost it is necessary to determine the active material weight (weight of iron, \( m_{Fe} \), and weight of copper, \( m_{Cu} \)) and the total weight of the generator, \( m_c \).

The losses which determining the operating cost is defined mainly through the iron losses, \( p_{Fe} \), the losses in copper, \( p_{Cu} \) and total losses, \( \Sigma p \), of the synchronous generator.

4.1 The influence of the stator inner diameter variation, \( D \), upon the weights of the synchronous generator

The weights of iron, \( m_{Fe} \), of the synchronous generator is calculated as the sum of stator teeth weight, \( m_{d1} \), the stator yoke, \( m_{j1} \), the rotor poles, \( m_p \), the rotor yoke, \( m_{j2} \).

From the scientific literature it is known that the stator inner diameter, \( D \), affects the length of the synchronous generator, given by the polar step, \( \tau \), according to the relation (5) and:

\[
i = \lambda \cdot \tau \quad (12)
\]

The weight of the stator teeth, \( m_{d1} \), is dependent on the length of the generator, the weight of the stator yoke, \( m_{j1} \), is dependent on the diameter of the generator.
stator and length generator, the weight of the rotor pole, \( m_p \), is dependent on the length of the generator and the weight of the rotor yoke, \( m_j \), is dependent on the length of the generator. It results that the value of the stator inner diameter substantially influences the weight of iron, as shown in Figure 6, we presented the influence of variation of the stator inner diameter on the weight of iron, the weight of copper and total weight of the synchronous generator. The weights values represented in the figure are in units reported [u.rap.] to the weights from classical designing.

\[
\begin{align*}
\text{Fig. 6 The influence of the stator inner diameter variation upon the weight of iron, copper and total mass}
\end{align*}
\]

An increase of the stator inner diameter from the value \( D_g = 470 \text{ mm} \) to \( D = 609.6 \text{ mm} \) that is about 30%, leads to a decrease of the weight of iron with 9,19%. This is possible because the increased diameter has as effect decreased length of the generator and the final result, reducing the weight of iron.

The weight of copper \( m_{Cu} \), is formed by the weight of copper of the stator windings, \( m_{Cu_1} \), of the excitation windings, \( m_{Cu_e} \), and of the windings of damping \( m_{Cu_d} \). Such weights are dependent on the diameter of the stator through medium length of half of the average length of coiling, \( l_{meds} \), of the average length of excitation winding of coiling, \( l_{mede} \), and of the damping bar length, \( l_b \).

Thus, an increase of the stator inner diameter from the value resulted of classical designing, to the value resulted in optimal designing, lead to a decrease in the total mass of the copper, \( m_{Cu} \), with 11,1%. The total weight, \( m_t \), of the synchronous generator, resulted in optimal designing, decreases with 9,71% compared to the weights resulted from the classical designing.

In the field of analysis of the value of the stator inner diameter, presented in graphic (330,5 mm ÷ 609,6 mm), taking as reference of the diameter value obtained from conventional designing (609,6 mm), it is found that the total weight of generator increases with 38%, so a significant increase with unwanted implications in the chosen objective function.

4.2 The influence of the stator inner diameter variation, \( D \), upon the losses of the synchronous generator

Because the weight of the synchronous generator is influenced by variation of the stator inner diameter, it follows that and losses in the generator are also influenced.

In Figure 7 we present the influence of variation of the stator inner diameter, \( D \), upon the iron losses, \( p_F \), the losses in copper, \( p_{Cu} \), and total losses, \( \Sigma p \), the values are reported in units (u.rap.) to the values determined from classic designing.

\[
\begin{align*}
\text{Fig. 7 The influence of the stator inner diameter variation upon the losses of the synchronous generator}
\end{align*}
\]

Compared to the results obtained in classical designing, a optimal designing has led to the values of iron losses, \( p_F \), lower with, 6,43%, at values of losses in copper, \( p_{Cu} \), lower with, 7,86% and at values of total losses, \( \Sigma p \), lower with, 3,58%.

Although the total mass, \( m_t \), of the generator decreased with 9,71%, the total losses, \( \Sigma p \), are smaller (3,58%), because these losses is found only the active material of the generator (iron and copper), not in the total weight of the generator.

4.3 The influence of the stator inner diameter variation, \( D \), upon the cost of the synchronous generator

The weight materials, \( m_w \), influences the manufacturing cost, \( C_f \), and the total losses, \( \Sigma p \), influence operating cost, \( C_e \), throughout the normed life of the synchronous generator. It follows therefore that the value of the stator inner diameter, \( D \), influence the manufacturing cost, the operating cost and the total cost, \( C_t \), of the synchronous generator. This influence is presented in Figure 8.

For the optimal value of the stator inner diameter, \( D = 609.6 \text{ [mm]} \), results a decrease of the manufacturing cost, \( C_f \), with 9,88%, of the operating cost, \( C_e \), with 1,23% and the total cost , \( C_t \), with 4,3% compared to the costs resulted from classic designing, where the value of the stator inner diameter was \( D_g = 0,470 \text{ [mm]} \).
5 The analysis of the stator inner diameter variation, $D$, upon the efficiency of the synchronous generator

A performant synchronous generator has as main parameter, efficiency, and its value must be as large, as possible defined by the relation:

$$\eta = \frac{S_N \cdot \cos \phi}{\cos \phi + \sum p}$$  \hspace{1cm} (13)

In relation (13) $S_N$ is the power of the generator, $\cos \phi$ is the power factor.

The influence of the variation of the stator inner diameter, $D$, upon the efficiency is presented in Figure 9, where values are presented in reported units [u.rap.], at resulted values in classical designing.

The optimal value of the stator inner diameter, resulted in the classic designing, determines an increase in efficiency with 0,00173 [u.rap.] ie with 0,173% compared to the value resulted in the classical designing.

4 Conclusion

From the graphs analysis that have resulted from the running of the optimal design program we conclude that the choice of values for the stator inner diameter, $D$, leads to fulfillment or not of the objective function chosen.

From the analysis made, it follows that the value of the stator inner diameter, resulted in optimal design, greatly influences the value of synchronous longitudinal reactance, the transient and over-transient reactance being less influenced. The same affirmation is valid for transversal synchronous reactance, over-transient and permanent regime, too.

Regarding the influence of the resulted value in the optimal designing of the stator inner diameter, $D$, upon the inverse and homopolar reactance, from the analysis it follows that higher values of the diameter have a beneficial influence, in more pronounced way, the homopolar reactance, and even less, the inverse reactance.

Because, for optimal designing, the value of the synchronous longitudinal reactance, $x_d$, is strongly influenced by the value of the diameter, the analysis it shows that an inner diameter of the stator determined the low values, especially in the balanced three-phase short circuit current $I_{d3}$.

Because a larger diameter of the stator, determined a higher rate of the reactance value, it follows that, the optimum of the transient current value is smaller than the one obtained in classical designing.

Regarding the cost of the generator a larger diameter determines a weight of copper, iron and total weight much smaller than a smaller diameter, which determines a greater length of the generator and thus larger weights.

At the same time, a larger diameter, determines lower losses and implicitly reduced costs.

In conclusion, a higher value of the stator inner diameter, $D$, determined from the optimal designing has led to the achievement of proposed objective function (least cost), satisfying to a certain extent, and both the functional criterion of safety and the economical one.

References: