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Research Article

DESIGN IMPROVEMENT OF A 2 MVA SYNCHRONOUS MACHINE BY USING PARTICLE SWARM OPTIMIZATION

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Abstract: *In this article; The step-by-step design of a 3-phase salient synchronous generator and efficiency optimization with particle swarm optimization technique are investigated. Unlike other studies in the literature, a system has been studied to minimize mathematical equation errors by using specific loading parameters that simplify the design process. It has been tried to obtain a program structure that minimizes programming problems by minimizing the number of variables used in the design. With the optimization of the specific loading parameters, the effects on the machine volume, cost and efficiency were examined. As a result, it has been observed that the productivity value increased with particle swarm optimization. In addition, the decrease in machine volume provided an advantage in terms of cost.*

Keywords: *sycnchronous machine, machine design, particle swarm optimization*

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1. Introduction

Synchronous machines are widely used in power generation besides industrial applications in general Hydroelectric power plants are the most widely used area in power generation. They are used as round-pole high-speed turbo alternators in thermal power plants. It has also been used in wind power plants in recent years [1]. Synchronous generators are electrical machines that are mostly preferred to provide high capacity power generation and produced at different power levels from a few kVA to hundreds of MVA [2]. Synchronous generators are divided into two types which are salient-pole and round-pole synchronous generators based on their polar structures. Salient pole synchronous generators are generally used in hydroelectric power plants. They are preferred in low speed and high power applications. The aim of the design is to achieve maximum performance with minimum cost. However, providing minimum loss at low cost is one of the most important parts of the design. Simply minimizing the cost can result in high maintenance costs for the machine thus, the losses increase. For these reasons, there must be a balance between the cost and losses for the optimum design of the machine taking into account the application area [3]. Design optimization of electrical machines consists of two stages: design and optimization. In the design phase, the aim is to find the appropriate schema by searching for multidisciplinary analyzes or designs. In the optimization phase, the aim is to improve the performance of the proposed machine in the design phase with optimization methods. [4]. In this study, the efficiency of a three-phase generator is optimized by using the Particle Swarm Optimization (PSO) technique. In the study of Elez et al., optimization method for slot skew was applied in order to reduce damper bar losses and reduce total harmonic distortion of line voltage in salient pole synchronous generator. It has been concluded that with this optimization method, the damper bar losses can be reduced by 7 times and the total harmonic distortion can be reduced below 1%. [5]. In [1], the shape of the rotor is optimized to facilitate the assembly of excitation windings. The new rotor shape has greatly reduced the maintenance and repair costs of the synchronous machine [1]. The parameter calculation and specific loading options used in the design are also utilized in the compatibility design study of Oo and Thant's round-pole synchronous generator. In this study conducted in 2019, they examined the relationship between the parameters that would improve the design by using specific loading options [6]. In another study [7], an optimization method is proposed to increase the efficiency of a salient pole synchronous generator using simulated annealing algorithm. Bell and Anpalahan optimize the rotor design in their works with the limitations placed on the main rotor geometry of a dislocated pole synchronous generator [8]. As a result of this optimization, the reducing effect on the total cost is observed. In [9], the topology of the shock absorber winding is investigated to increase the general performance of a 4 MVA salient-pole synchronous generator using conventional shock absorber winding. In this research, general algorithm optimization is used for improvement by performing finite element analysis [9].

Unlike the other studies in this paper, specific loading choices that simplify the design process are explained. Complex mathematical equations are avoided by specific loading selections. Here, PSO has been carried out by considering the parameter limits of the salient-pole synchronous machine.

2. Design of a synchronous generator

The designs of the salient pole generators are different from each other based on their power and usage areas. The design process usually starts with the calculation of the main dimensions. The first dimension to be chosen in the design is specific loading. The choice of specific electrical load, which is an empirically determined magnitude, varies between 20.000 A/m and 50.000 A/m for salient-pole synchronous machines, and between 50.000 A/m and 100.000 A/m for turbo generators [10]. Specific magnetic loading selection, which is an empirically determined magnitude, varies between 0.52 wb/m^2 and 0.65 wb/m^2 for salient-pole synchronous machines, while turbo generators range from 0.55 wb/m^2 to 0.65 wb/m^2 [11]. The inner diameter and axial length of the stator are the main dimensions of the machine. The parameters of the synchronous generator to be designed are given in Table 1.

Table 1. Parameters of synchronous generator

Parameter name	Variable	Value
Rated Power	kVA	2.000
Power Factor	-	0.8
Number of Poles	-	24
Rated Voltage	V	6.300
Frequency	Hz	50
Speed	rpm	250
Temperature	^{0}C	75

By using these values, the apparent power of the machine is obtained as follows

$$\mathrm{P_{sn}} = \mathrm{C_0 \ x\ D^2 \ x\ L\ x\ n_s} \tag{1}$$

where P_{sn} ; apparent power of the machine (kVA), C_0; utilization coefficient (kVA.dak/m^3), D ; stator inner diameter (m) and L ; the stator axial length(m). The synchronous speed of the machine is given by

$$\mathrm{n_s} = \frac{120*f}{P} \tag{2}$$

where n_s, f, and p are the synchronous speed of the machine as rpm, frequency and the number of pole, respectively. The volume of the machine can be calculated from (1) as follows

$$\mathrm{D^2L} = \frac{\mathrm{P_{sn}}}{\mathrm{C_o.\ n_s}} \tag{3}$$

The stator inner diameter can be found by the following equation

$$\mathrm{D} = \frac{\mathrm{V_a}}{\pi.\mathrm{n_s}} \tag{4}$$

where V_a is the circumferential speed. Its unit is m/s. The circumferential speed upper limit is 80 m/s for salient-pole synchronous machines [12].
Stator axial length is shown as follows

$$\mathrm{L} = \frac{\mathrm{D^2L}}{\mathrm{D^2}} \tag{5}$$

The total stator length must be 1 cm longer than the axial length so that the resulting flux remains between the stator and rotor as follows [13].

$$\mathrm{L_{top}} = \mathrm{L} + 0.01 \tag{6}$$

The net stator iron length is the length of iron remaining when five cooling channels whose wides are 1 cm are removed from the total length as follows [13]

$$\mathrm{L_i} = \mathrm{L_{top}} - (\mathrm{z_k} * \mathrm{b_k}) \tag{7}$$

where $\mathrm{z_k}$ and $\mathrm{b_k}$ are the number of the cooling channels and the cooling channel width whose value is usually taken as 1 cm, respectively [13]. The number of the cooling channels can be found by the following equation

$$\mathrm{z_k} = \frac{\mathrm{L_{top}} * 10^{-2} * 5}{6} \tag{8}$$

$\mathrm{b_k}$ in equation (7) is the width of the cooling channel. Usually its value is taken as 1 cm.

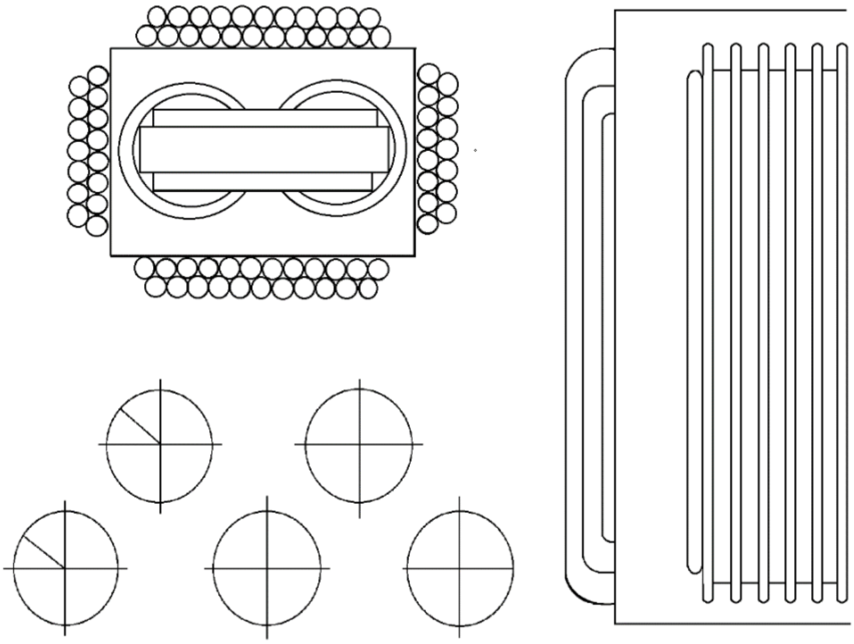

Figure 1. Detailed representation of the cooling channels [14].

The length of the air gap between the rotor and the stator is an important parameter that greatly affects the performance of the machine. Air gap length; depending on the pole step, it can be expressed by equation (10) [10].

$$\tau = \frac{\pi * \mathrm{D}}{\mathrm{p}} \tag{9}$$

$$\mathrm{l_g} = (0.012 \sim 0.016) * \tau \tag{10}$$

where τ ; pole pitch (m), p ; the number of the poles, l_g; length of the air gap (m).

Another parameter that affects the performance of the machine is the number of slots. The correct selection of the slot number also affects the cost of the machine. Therefore, it is necessary to pay attention to the selection of the number of slots per phase pole. Generally, the number of slots per phase pole is taken between 3 and 4 for salient pole synchronous machines [10].

$$\mathrm{N_s} = \mathrm{m} * \mathrm{p} * \mathrm{q} \tag{11}$$

where $\mathrm{N_s}$ is total number of slot. Slot step y_s (m) value is shown by

$$\mathrm{y_s} = \frac{\pi * (\mathrm{D} + 2 * \mathrm{l_g})}{\mathrm{N_s}} \tag{12}$$

There are boundary conditions for the slot step. These are given as follows:

$\mathrm{y_s} \leq 25\ mm$ for low voltage machines, $\mathrm{y_s} \leq 40\ mm$ for machines up to 6 kV, and $\mathrm{y_s} \leq 60\ mm$ for machines up to 15 kV [10]. The flux density in the teeth should not exceed 1.8 T. The slot width should not be less than 6 mm due to the production reasons.

$$\mathrm{b_o} = \mathrm{y_s} * 0.4 \tag{13}$$

where b_o (m) is the slot width.

$$\mathrm{A_{slot}} = \frac{6 * \mathrm{W_a} * \mathrm{I_{phase}}}{\mathrm{N_s} * \mathrm{K_{fill}} * \mathrm{j_s}} \tag{14}$$

where A_{slot} (m^2) , W_a, I_{phase} (A), N_s, K_{fill}, and j_s (A/mm^2) are the slot area, the number of turns per current path, phase current, the number of the slot, the slot filling factor, and the stator current density, respectively. K_{fill} is an empirical expression and can be taken between 0.35 and 0.6. Slot height is a

$$h_s = \frac{A_{slot}}{b_o} \tag{15}$$

The slot height can be defined by adding the rim height to be taken as 5 mm [12]

$$h_o = h_s + 0.005 \tag{16}$$

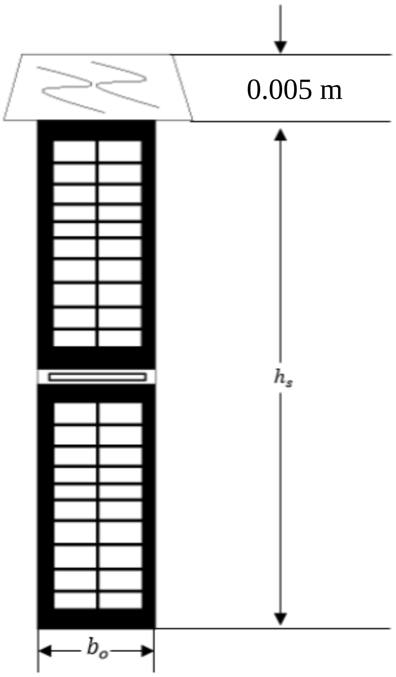

Figure 2. Slot width and height [13].

Stator yoke height is shown by

$$h_{ys} = \frac{B_g}{B_{ba}} * \frac{\tau}{\pi} \tag{17}$$

where B_g (T) and B_{ba} (T) are the flux densities in the air gap and stator yoke, respectively. B_g is taken in the range 0.8 to 1.05 T for salient-pole machines [12]. B_{ba} is also taken as 1.08 T [13]. The stator yoke height is used to calculate the stator outer diameter (D_s).

$$D_s = D + 2 * h_o + 2 * h_{ys} \tag{18}$$

In the design process, another parameter to be considered is the stator and rotor current densities. High current density means lower conductor, lower cost, higher temperature, more copper loss and lower slot area. The current density of the stator conductor is chosen between 3 A/mm^2 and 5 A/mm^2, and the current density of the rotor conductor is between 3 A/mm^2 and 6 A/mm^2. The cross-sectional area current density of the stator conductors can be calculated from the phase current value.

$$as = I_{phase}/j_s \tag{19}$$

where I_{phase} is the phase current and j_s is the current density. The cross-sectional area current density of the rotor conductors is calculated from its value as seen in equation (20).

$$af = I_f/j_r \tag{20}$$

where I_f is the field current and j_r is the rotor current density. Total number of the conductors in the stator is shown as follows

$$Z = \frac{\pi * D * ac}{I_{phase}} \tag{21}$$

The number of the conductors in one slot is also calculated by

$$Z_o = \frac{Z}{N_s} \tag{22}$$

where Z_o must be an integer value and be between 10 and 13 on the 2 MVA machine under consideration [13].

The design is completed by calculating the efficiency of the machine. The losses of the machine are considered in the efficiency calculation. These losses are as follows:

- Stator copper losses
- Rotor copper losses
- Additional losses due to the construction parts between the facade connections
- Iron losses
- Iron loss in teeth
- Pole foot surface losses
- Friction losses

The efficiency can be expressed by using the losses as follows

$$\eta = \frac{P_o}{P_o + P_T} \tag{23}$$

where P_o is the output power and P_T is the total losses.

3. Particle swarm optimization method

Optimization is the process of obtaining the most reasonable result by observing certain limitations for some objectives. It is an idea development tool. The goal of the optimization is always to achieve the best. One of the methods used in solving the optimization problems is Particle Swarm Optimization (PSO). PSO is an optimization method introduced by Kenedy and Eberhart in 1995 based on the movement of fish and insects as flocks [15]. It has been observed that the random actions of the animals moving in herds enable them to reach their goals more easily in some situations such as food and safety. PSO is based on the social information sharing between the individuals [16]. PSO which is an algorithm influenced by herd intelligence has been used for the optimization problems in various fields such as electromagnetics, design systems, manufacturing, and electrical power systems [17]. It is also a method used in the control of nonlinear systems. It gives successful results when applied to the systems with many parameters and multivariate [18]. Each of the individuals in the PSO has a different speed value. At each step, individuals renew their speed values according to the individual in the best position [19]. Position and velocity vectors are expressed as $(x_{i1}, x_{i2}, \dots, x_{iD})$ and $V_i = (v_{i1}, v_{i2}, \dots, v_{iD})$, respectively. Each particle updates its position and speed based on its best position (pbest) and the best position of the whole cluster (gbest). After finding the best two values in each step, it updates itself according to the following equation [15]:

$$v_{id}^{t+1} = w * v_{id}^{t} + c_1 * r_1 * \left(pbest_{id}^{t} - x_{id}^{t}\right) + c_2 * r_2 * \left(gbest_{id}^{t} - x_{id}^{t}\right) \tag{24}$$

$$x_{id}^{t+1} = x_{id}^{t} + v_{id}^{t+1} \tag{25}$$

where $i = 1,2, \dots, NP$ and NP, w, c_1 and c_2 are scaling factors. NP determines the size of the flock, w is the inertia weight value for each iteration, c_1 and c_2 are the relative influence of the cognitive and social components, respectively. $r_1$and r_2 are any random numbers in the range between 0 and 1. x_{id}^{t}, v_{id}^{t}, $pbest_{id}^{t}$ are the position, speed and personal best values for d. position in size of t. iteration of the i. particle, respectively. Under the same conditions, the best particle of the whole flock is $gbest_{id}^{t}$. In this study, c_1 and c_2 learning factors are taken randomly to achieve better performance of the optimization.

Since there is no need for derivative information in PSO, it differs from the other optimization techniques. PSO is also easy due to the small number of the parameters that need to be adjusted compared to the other algorithms [20].

The parameters of the PSO applied in this study are given in Table 2.

Table 2. PSO Parameters

Parameter name	Variable	Value
Cognitive component	c_1	0.12
Social component	c_2	1.2
No. of particles	n	100
No. of iterations	NP	1000
Minimum inertia weight	$w_{\min}$	0.4
Maximum inertia weight	w_{max}	0.9
Dimension	dim	3

4. Optimization of the synchronous generator

Before the optimization process, the efficiency value of the synchronous generator was calculated as 94.63%. Efficiency was chosen as the target parameter while optimizing. PSO method is preferred for the optimization. The limits of the parameters that will affect the efficiency are determined for the optimization process. In this study, the limiting parameters and limits are given in Table 3.

Table 3. Some parameters affecting the efficiency and their ranges.

Parameter	Their ranges

$\boldsymbol{B_{av}}$	0.52 wb/m^2-0.65 wb/m^2
ac	20,000 A/m -50,000 A/m
$\boldsymbol{V_a}$	30 m/s -80 m/s

Along with these limits, the optimization process is realized by considering the values of the scaling factors. The values of the c_1 and c_2 learning factors are taken as 0.12 and 1.2, respectively. As a result of the optimization process, the efficiency of the machine reached to 94.84%. The efficiency graphics are given before and after the optimization process in Figure 3 and 4, respecively.

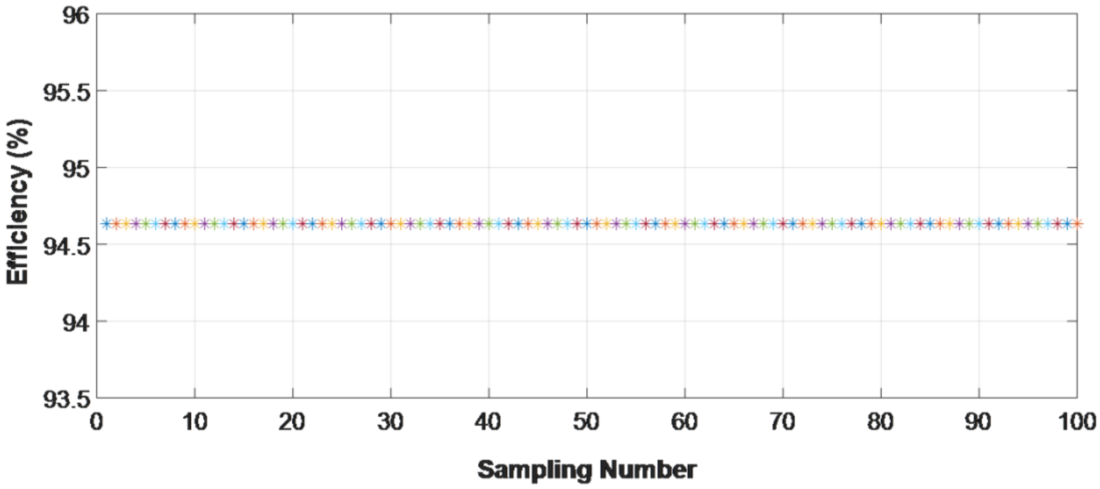

Figure 3. The efficiency of the synchronous generator before the optimization.

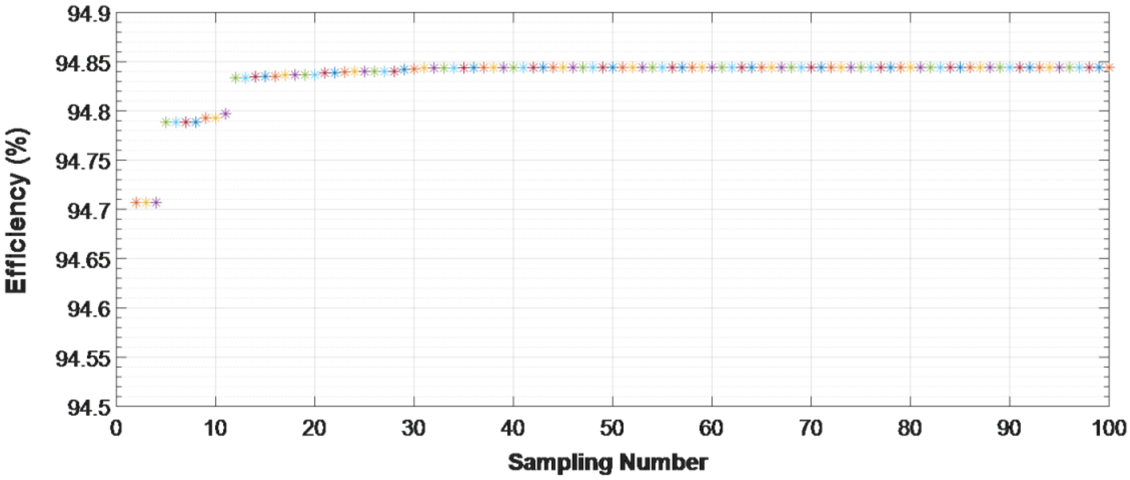

Figure 4. The efficiency of the synchronous generator after the optimization.

In addition to the improvement in efficiency with the optimization process, B_{av}, ac, V_a, pole step, number of turns per phase and total loss values are also optimized. The values of the parameters before and after optimization are given in Table 4.

Table 4. Optimized parameter results

Parameters	Pre-Optimization Value	Post Optimization
$\boldsymbol{B_{av}}$ (wb/$\boldsymbol{m^2}$)	0,52	0,55
ac (A/m)	43850	43720
$\boldsymbol{V_a}$ (m/s)	31,5	30,79
Pole pitch (m)	0,315	0,307
The number of turns per phase	305	295
Total losses (W)	90729	86978
Efficiency (%)	94,63	94,84

5. Conclusions

In this paper, the design calculation of a 2 MVA synchronous machine has been made. The designed synchronous machine has been optimized by PSO method. Unlike the other studies in the literature, the complexity of the mathematical expressions in the design process is removed by using specific loading selection parameters in this work. In this way, the design of the synchronous machine to be used according to the application area can be expressed more clearly. In addition, optimization was applied to specific loading parameters. By optimizing the machine, the $\mathrm{B_{av}}$ value has changed, increasing the steady state stability. The change of ac value also reduces the copper losses, stray load losses and the number of armature conductors. On the other hand, the change in the value of the pole pitch provides the air gap length, pole body width and yoke height to decrease. Besides with the decrease in the number of the windings per phase, the volume of the machine also reduces. As a result, it is seen that the reduction in the volume of the machine provides a cost benefit. With the increase in the efficiency value, the intended purpose of the design is achieved.

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