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OPTIMAL DESIGN OF A WOUND ROTOR SYNCHRONOUS GENERATOR USING GENETIC ALGORITHM

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Abstract* – The manufacturers are tempted to reduce the amount of active materials in the devices in order to lower the material bill. However, reducing the weight of the devices directly affects the energy efficiency. In this paper, a solution to this problem is proposed for the case of synchronous wound rotor generators. The trade-off between cost and efficiency is formulated as a constrained optimization problem and solved using a Genetic Algorithm. The cost optimization of three different machines is carried out through various design approaches. The proposed approach always gives better results than the classical approach concerning the global cost of the range.

Introduction

The recent rise in the cost of raw materials is motivating the manufacturers of electrical machines to improve the designs of their devices. The manufacturers are tempted to reduce the amount of active materials in the devices in order to lower the material bill. However, reducing the weight of the devices directly affects the energy efficiency, and therefore goes against the current trend and European suggestions [1], which recommend that the manufacturers increase the efficiency of their products. Manufacturers are thereby confronted with a constrained optimization problem: reducing the costs of devices and respecting the fixed efficiencies. In this paper we propose a solution to this problem for the case of a series of Wound Rotor Synchronous Generators (WRSG) using an optimization method based on Genetic Algorithm (GA).

The optimal design approach is used more and more often in the case of electromagnetic device design. This approach needs to accurately model various physical domains [2-3]. Magnetic, electric, thermal or mechanical models of the systems are often developed in order to design optimal devices respecting physical constraints from various fields of physics. The accuracy of the model and its execution time basically depends on the modeling complexity: 1D analytical model [3-6], electric circuit type model [3, 7-8] or Finite Element model [3, 9-10].

In this work, a 1D multiphysics modeling of the WRSG was adopted whose short execution time allowed coupling with a stochastic optimization method. A GA optimization technique was employed because it is well suited to a mixed-variable constrained problem and it allows searching for a global optimum. The complexity of the treated objective function also leads to choose a zero-order derivation method.

The modeling of the machine and then the optimization method will be detailed followed by the optimization results. The range optimization needs to introduce a new procedure, different from the classical range design approach used in industry. The introduced method compares favorably with the classical one for various test cases and permits rationalization of the optimal design of a series of machines from an industrial point of view.

Wound Rotor Synchronous Generator Model

The geometry of the studied WRSG is shown in Figure 1. The stator tooth width is constant except for the bottom and the slots' back side. The air gap is progressive and the rotor winding is ordered. The model is parameterized with eight variables, constrained within a fixed range, which are detailed in Table 1 with their original values.

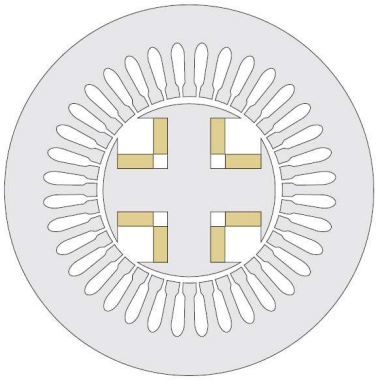

Fig. 1. Geometry of the WRSG studied with salient poles

Tab. 1. WRSG's initial variable values with their ranges

WRSG's parameters	Initial design	Range
Effective Power [kVA]	165	-
Outer stator diameter [mm]	390	[390,420]
Inner stator diameter [mm]	270.5	[255,290]
Slot diameter [mm]	317.5	[300,360]
Tooth width [mm]	10.2	[5,24]
Rotor pole width [mm]	86.5	[70,100]
Rotor pole opening factor	0.7045	[0.6,0.8]
Machine length [mm]	410	[210,420]
Conductor number	6	[5,12]
Cost [€]	790	-

Electromagnetic Modeling of the WRSG

The fundamental quantity used for the machine modeling and optimization is the line voltage (peak or rms value). This voltage waveform is considered purely sinusoidal. Knowledge of this voltage, neglecting the winding resistance, allows determination, via integration, of the amplitude of the flux through the WRSG windings.
The next step consists of determining the amplitude of the fundamental of the air gap magnetic flux density which is directly linked to the flux amplitude as a function of air gap geometry (length of the air gap and Carter's coefficient).
Next, the local value of air gap magnetic flux density under the poles is determined. To do this precisely, one needs to know the relations used to determine the "exact" waveform of the air gap magnetic flux density under one pole from the fundamental air gap magnetic flux density value and reversely, as depicted in Figure 2.

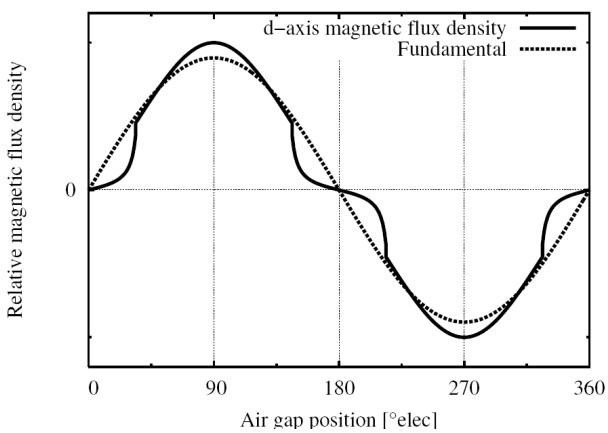

Fig. 2 - Exact waveform of air gap magnetic flux density and its fundamental due to d-axis stator current reaction

The magnetic flux density local value under the whole pole permits computation of the flux through the pole and the magnetic flux density inside the pole. Then, using the flux conservation law, one can determine the magnetic flux density's values in the various elements of the magnetic parts of the stator: in the teeth and in the stator back iron (for the latter the minimal and maximal values are computed).

This computation gives the magnetic field in the various parts of the WRSG: inside the air gap, the relation between magnetic field and magnetic flux density is linear, it is the vacuum magnetic permeability; for the other elements, information about the iron sheets (magnetic characteristic: magnetic flux density at saturation, permeability in linear and saturated areas) permits determination of the correspondence between flux density and magnetic field.

The computed magnetic field allows determination of the magneto motive forces (or Ampere-turns, mmf) applied to each element of the WRSG: the air gap, the pole, the teeth and the stator back iron. The summation of all the mmf gives the mmf value for the no-load working point ε_0.

All that is described in the previous paragraphs corresponds to a no-load running, and so now the influence of the current flowing in the stator when loaded must be determined. To determine this effect, it is considered that the mmf ε to be supplied for a given working point (emf E and current I) is the sum of two mmf: ε_0 that should be supplied to obtain the no-load emf E and ε_{cc} that should be supplied to deliver the current I in short-circuit condition (1).

$$\varepsilon = \varepsilon_0 + \varepsilon_{cc} \text{ [A.turns]} \tag{1}$$

The determination of ε_{cc} is detailed as follows. The current flowing in the stator windings produces a mmf which will be called the armature current reaction. From this quantity, the air gap magnetic flux density due to the armature reaction is deduced. Then, according to the principle detailed before, the fundamental of this magnetic flux density noted B_{1d} is determined. B_{1d} depends only on ε_{cc}.

Potier's method, described in [11], needs to be applied according to the following considerations. In short-circuit, the air gap magnetic flux density value is low, so that the machine is not saturated; on the contrary, it is working under linear conditions. As a consequence it can be stated that the mmf ε_{cc} needed to obtain the air gap magnetic flux density is directly proportional to this very value. To determine the proportionality coefficient, a linear relation linking the mmf ε_{ent} to be applied to the air gap and the magnetic flux density inside this one is:

$$\varepsilon_{ent} = \frac{B_{ent}.e.carter}{\mu_0} \text{ [A.turns].} \tag{2}$$

Where B_{ent} is the fundamental amplitude of the air gap magnetic flux density, e is the air gap length, $carter$ is the Carter's coefficient of the air gap.

With a simple proportional relation, one can deduce:

$$\varepsilon_{cc} = \varepsilon_{ent} \frac{B_{1d}}{B_{ent}} \text{ [A.turns].} \tag{3}$$

From this expression, the value of the mmf needed according to relation (1) is computed.

Losses and Thermal Model

To ensure normal working conditions of the machine, the thermal behavior has to be studied. First the different kinds of losses occurring in the machine must be evaluated to give the input parameters of the thermal model that yields the stator and rotor temperatures.

1/ Losses' Estimation

The classical copper losses in stator and rotor windings are computed in a traditional way with (4).

$$P_{copper} = 3R.I^2 \text{ [W]} \tag{4}$$

The resistivity temperature dependence is taken into account, which leads to a coupling between loss estimation and temperature computations. This coupled system of equations is solved using a fixed point method. The iron losses can be estimated because the magnetic flux density has been determined in all the magnetic parts. In the first harmonic approximation the iron losses appear only inside the stator. These losses are computed in the teeth and stator back iron, using (5).

$$P_{iron} = k_{iron}\left(\frac{B}{1.5}\right)^2 \text{ [W/kg]} \tag{5}$$

which is valid at 50 Hz. k_{iron} is the specific iron loss for a 1.5 T induction at 50 Hz for a 4-pole machine. Finally the mechanical losses corresponding to the windage losses and the bearing losses are evaluated with the correlation (6).

$$P_{mec} = k_{mec}\Phi_{out}{}^{4.5} \text{ [W]} \tag{6}$$

Where k_{mec} are the mechanical losses for a given stator outer diameter and Φ_{out} is the actual stator outer diameter. Knowing the different losses, the efficiency, as defined by [12], is computed.

2/ Thermal Modeling

As soon as the losses are determined the temperature increase in the stator and rotor are evaluated using a formulation derived from experimental correlations resulting from a wide experimental campaign. Either the stator or rotor temperature increase is evaluated with (7).

$$\Delta T = \frac{P_{copper}}{eff_{temp}\left(\Phi_{out}, L_{stack}\right)} \text{ [K]} \tag{7}$$

Where eff_{temp} characterizes the ability of evacuating the heat generated by losses; and it depends on machine external dimensions: the stator outer diameter Φ_{out} and the stack length L_{stack}. Substituting the stator or the rotor copper losses to P_{copper}, one can determine respectively the stator or rotor temperature increase.

Optimization Problem

Genetic Algorithm (GA) has been widely used in electrical machine optimization [13]. It can find the global optimum, and can easily deal with non-linear constraints and complex cost functions; this is

why it is used in this study. The cost function, expressed in (8), is determined by the sum of the copper and iron weight multiplied by their respective material cost [5, 7, 9].

$$total\_cost = \sum weight * material\_cost \tag{8}$$

It should be noted again here that there are eight design variables given in Table 1 with their respective ranges to be considered in the optimization. The optimization problem mixes continuous and discrete variables. Discrete variables are handled using the round operator after the crossover and mutation process [14]. The constraints to be considered are maximum temperature increase and minimum efficiency listed in Table 2, and they are handled via penalty functions as in [5].

Tab. 2 – Optimization constraints on output quantities

Stator temperature rise	< 125K
Rotor temperature rise	< 125K
Efficiency	η_{iec} > minimal efficiency

Optimization Results

Several optimizations were run to minimize various objective functions. A set of three machines covering a range of powers was considered for optimization. The three machines had power ratings of 125 kVA, 165 kVA, and 180 kVA. The goal of the consideration of a series of machine size is to show the interest of considering an ensemble of machine size when trying to optimize machines. First, the three WRSGs' costs are optimized separately. This approach leads to three different stator cross section geometries. This is unacceptable for industrial applications because it leads to unacceptable cost of production tools. Next, a classical range design approach is applied to determine a series of machines in which the cross section geometry is identical for the three WRSGs. Finally, new objective functions are introduced that hold for the specifications of the whole series of machines at once.

Independent Optimization of Three Different Machines

The three machines were first optimized independently. The cost is minimized respecting the minimum efficiencies of 91.6%, 91.7%, and 91.7% respectively for the 125, 165, and 180 kVA WRSGs. The results are given in Table 3 and the convergence of the algorithm is presented in Figure 3.

Tab. 3 - Machine characteristics resulting of independent optimizations of the WRSGs

variables	125 kVA	165 kVA	180 kVA
Outer stator diameter [mm]	393.7	420	420
Inner stator diameter [mm]	255.2	276.9	278.9
Slot diameter [mm]	311	326.1	331.5
Tooth width [mm]	11.1	12.9	12.4
Rotor pole width [mm]	89	100	96.9
Rotor pole opening factor	0.748	0.7415	0.7415
Machine length [mm]	285.2	331.7	349.9
Conductor number	8	6	6
Stator temperature rise [K]	83.0	125	125
Rotor temperature rise [K]	124.8	125	125
Efficiency [%]	91.60	91.79	92.34
Cost [€]	563.20	686.72	757.56

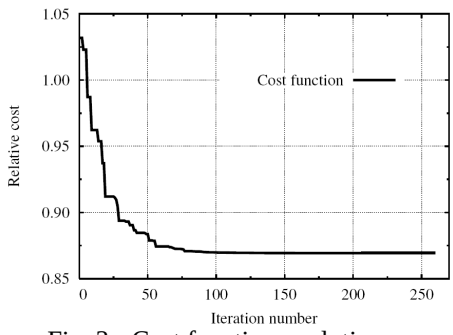

Fig. 3 - Cost function evolution vs. iteration number for the 165 kVA WRSG. The results are normalized according the initial 165 kVA design

It can be noted in Table 3 that for the 165 and 180 kVA machines the constraints on rotor and stator temperature increases are saturated as well as outer stator diameter. The 125 kVA WRSG has two saturated constraints: the rotor temperature increase and the efficiency. These results are in good agreement with usual remarks: larger machines are often very efficient but limited by temperature constraints. On the other hand smaller machines are known to have lower heating but poorer efficiencies.

Classical Design Approach Covering a Range of Powers

When designing a series of machines in an industrial environment, an important constraint is the cost of production. To reduce investment costs, a strong constraint is introduced: all the machines having the same outer diameter must have the same cross section geometry. This means that the three machines of our range of powers differ only in their stack length and their conductor number. Usually the largest machine cost is optimized and then the stack length is adjusted as well as the conductor number in order to obtain the two smaller power machine designs.

Thus starting from the 180 kVA design of Table 3, two-variable optimizations (stack length and conductor number) are carried out but for the powers of 125 kVA and 165 kVA. The results are given in Table 4.

Tab. 4 - Machine characteristics resulting from the classical design approach: adapting the largest machine to obtain the two smaller power machines

variables	125 kVA	165 kVA	180 kVA
Outer stator diameter [mm]	420		
Inner stator diameter [mm]	278.9		
Slot diameter [mm]	331.5		
Tooth width [mm]	12.4		
Rotor pole width [mm]	96.9		
Rotor pole opening factor	0.7415		
Machine length [mm]	261.8	349	349.9
Conductor number	8	6	6
Stator temperature rise [K]	87.1	97.8	125
Rotor temperature rise [K]	90.3	106.9	125
Efficiency [%]	91.61	92.53	92.34
Cost [€]	594.52	755.85	757.56

One can think of starting from the cross section design of the smallest optimized machine and then having the stack length increased and the conductor number changed in order to reach the specified powers of 165 kVA and 180 kVA. An optimization was performed according to this idea but the algorithm was unable to find any solution. Indeed a feasible solution for the largest machine would be to enlarge the stack length beyond the upper fixed limit: the optimal stack length of the largest machine would be 0.478 m. This confirms the approach adopted by manufacturers: designing the largest machine and then having the stack length shortened. This way, one can be sure to keep all the machines of the series within a fixed volume. But fixing the cross section geometry from the largest optimized WRSG may not be the most optimal solution when considering the cost of the entire range.

Simultaneous optimization of a series of machines at once

It is here proposed to optimize the cost of the entire range considering the three machines at the same time. The objective function to minimize is then a weighted sum (9) of the individual costs of the three

machines. This method is similar to the annual energy production (AEP) optimization when considering a wind generator [5, 10].

$$total\_cost = \sum_{i=1}^{3} weight\_i * machine\_i\_cost . \tag{9}$$

The weighting factors correspond to the repartition of the sales inside the considered range. Thus the cost function to minimize is the average cost per machine.
The design variables are therefore changed. Instead of one stack length and one conductor number, there are now three stack lengths and three conductor numbers, one stack length and one conductor number per machine. Three different cases are studied, corresponding to three different sets of weighting factors given in Table 5.

Tab. 5 – Weighting factors for the three studied cases

	125 kVA	165 kVA	180 kVA
Case I	8/10	1/10	1/10
Case II	1/10	8/10	1/10
Case III	1/10	1/10	8/10

The optimization results of the three cases are given in Table 6 along with the considered constraints. Moreover the savings due the new proposed method are given.

Tab. 6 – Optimal Machines' characteristics in case of non uniform sales

	Case I			Case II			Case III		
	125 kVA	165 kVA	180 kVA	125 kVA	165 kVA	180 kVA	125 kVA	165 kVA	180 kVA
Outer stator diameter [mm]	412			420			420		
Inner stator diameter [mm]	267.6			276.9			277.6		
Slot diameter [mm]	324.1			332.6			330.6		
Tooth width [mm]	12.1			12.3			12.4		
Rotor pole width [mm]	94.7			95.1			96.8		
Rotor pole opening factor	0.7472			0.7372			0.7427		
Machine length [mm]	266.2	360.7	394.8	266.1	306.6	355	261.3	348	352.1
Conductor number	8	6	6	8	7	6	8	6	6
Stator temperature rise [K]	82.3	93.3	125	78.6	125	111.7	86.7	97.3	125
Rotor temperature rise [K]	110.4	124.9	124.9	89.5	125	125	92.5	110.1	125
Efficiency [%]	91.60	92.53	92.40	91.89	92.00	92.59	91.60	92.51	92.35
Cost [€]	573.54	740.39	800.63	612.52	688.28	778.72	590.73	750.49	758.06
Mean cost per machine	612.93 €			689.75 €			741.09 €		
Saving compared to classical approach	- 2.24 %			- 6.78 %			- 0.07 %		

Whatever the chosen weighting factors, the proposed cost function gives better results than the classical design approach. This will give a non-negligible cost reduction for manufacturers. When

analyzing the cost of the optimized WRSGs, it can be observed that the heaviest weighted machine is that which is privileged during the optimization process. This also means that the saturated constraints are often those of the privileged WRSG as can be seen in Table 6. In case I the minimum efficiency is saturated for the smallest machine and the larger ones are constrained by their temperature increases. In case II the 165 kVA and 180 kVA WRSG are both limited by temperature increase. Finally in case III the largest WRSG is thermally constrained and the smallest one by its minimal efficiency.
As expected the cross section design resulting from the simultaneous optimization of the whole series depends on the sales' distribution. The differences in the results confirm the adopted approach.

Conclusion

A GA optimization process has been applied to wound rotor synchronous generators' design with the idea of minimizing the cost of the machine. First, three different WRSGs, differentiated by their power, have been independently optimized under geometrical, thermal and efficiency constraints. Then the three WRSGs' designs were considered from an industrial point of view which introduces a new geometric constraint: the cross section dimensions of the three WRSGs must be the same to avoid excessive investments in the production tool. Using this consideration a classical design approach is carried out and its results are compared with the results from the minimization of the newly proposed objective function. As shown, the new approach gives better results in all of the cases studied. Very few adjustments are needed for optimizing the whole range at once and the results show that the global optimization of the series can bring an important reduction of the global range cost. The method can be extended to series of any kind of electrical equipment through a straightforward process.

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