Optimization of a synchronous generator focusing on biomass cogeneration market (sugarcane industry)

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ABSTRACT - In recent years the sugarcane industries have invested on bagasse cogeneration in order to become energy self-sufficient and to export surplus electricity. This segment has special importance for these industries, firstly due to the extra profits coming from energy sale, secondly because it is green energy, once it helps to minimize CO2 emission and impacts on environment. Being so strategic, it is important driving more resources in developing of generators for this specific application with the purpose of improving their performance, aiming to design high efficiency generators with less active materials.
This proposed paper will present an optimization of a standard turbogenerator using genetic algorithm, in order to meet the maximum efficiency at the minimum cost, attending performance requirements for sugarcane application, like the main reactances and the short circuit ratio (SCR).
The utilization of genetic algorithm is justified here by its attested success on electrical machine optimization, due its ability to find global minima instead the local ones.
The problem showed on this paper is settled with multi-objective functions and a set of chosen constraints which is dependent on the generator's topology, like short circuit ratio for example, that defines the dimension of the air gap and consequently the volume of rotor and thus the generator costs.

1. INTRODUCTION

In the last decade, the world has witnessed the growing interest in an environmentally friendly alternative to producing electricity, with particular emphasis on the use of renewable and distributed generation.
Countries like India and Brazil, as larger producer of sugar cane, have a singular opportunity to expand their clean energy production just exploiting an existing resource more efficiently: the bagasse and the cogeneration.
This way, selling the produced surplus energy to the market becomes a second business and the bagasse, a byproduct of the main activity until now, becomes a fuel that must be rationally well spent. That is the purpose of getting a generation system with a larger efficiency.
As part of the system, the development of the turbogenerator must follow the evolution of the turbines, and although its greatest strengths in this effort are still in the refrigeration and insulation system improvements [1], nowadays there are tools which can help optimize the electrical design either.
The use of methodologies and optimization tools shall aim to meet both the customer who is purchasing the generator with increased efficiency by a minimum change in price, as the supplier, aiming to lessen the impact on the existing manufacturing process.
An optimization tool that has proven to be effective in design of electrical machines is the genetic algorithm, considering that is chosen an appropriate configuration. The genetic algorithm allows discrete variables to be successfully handled, preventing misleading results in points of local minimum [2].
Some electrical requirements must be considered in order to assure a proper behavior of electrical system. The short circuit ratio (SCR) for instance, which is correlated to static stability limits of the grid, needs to meet with the local codes, and once it defines the rotor volume [3] and consequently the generator size, the SCR is one of parameters that need to be controlled and kept in limits.
In short, the goal of this work is to take an existing standard generator (Table 1) and, keeping its main external dimensions: iron stack length, Ltv (Figure 1) and stator outer diameter, De1 (Figure 2), to optimize its geometry and enhancing its performance.

The main features of the generator are described in the following:

Tabela 1 - Generator characteristics

Description	Symbol	Value	Unit
Power	S	7.5	MVA
Voltage	U	13.8	kV
Frequency	f	60	Hz
Power Factor	cosφ	0.8	
Number of Poles	2p	4	
Phase	m	3	
Rotor Type		Laminated Cylindrical	
Armature Current	I	313.8	A

2. PROBLEM DEFINITION

This work consists to optimize, by genetic algorithm, the geometries, and electrical parameters of an existing standardized turbogenerator.

Keeping:

- Same external dimensions (Ltv and De1);

Respecting:

- Some chosen electromagnetic and thermal constraints which define a proper generator operation;
- Short circuit ratio (SCR) greater than 0.4.

And achieving:

- The best configuration with the minimum stator losses allowed by armature temperature rise;
- The minimum stator inductions.

The purpose of preserving the external dimensions of the machine is to reduce the impact on the existing manufacturing process, enabling to the company to maintain its production cost.

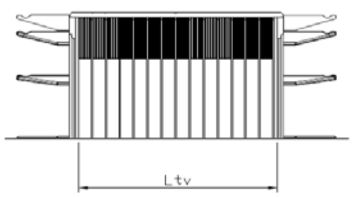

Figura 1 - Dimension of Pack of Steel Sheets

Concerned to the parameters, all of them are handled in their limits, taking into account the tests results of the existing generator, in order to achieve the best result for a specific frame. The independent variables, the input parameters mathematically defined as

$\vec{x} = (x_1, x_2, \ldots x_8)$

are considered discrete, some of them because of the process constraints or standardization such as the variation of the diameters and wires and slots dimensions, others due to the intrinsic nature of the parameter such as the number of slots, for instance.

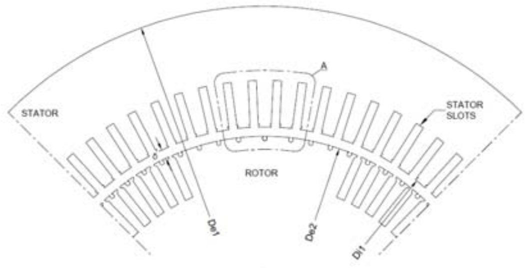

Figura 2 - Steel Sheet of Stator and Rotor -Main Dimensions

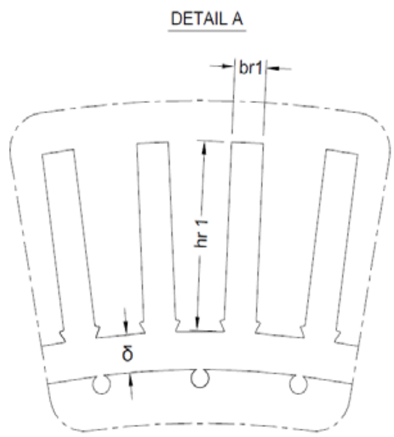

Figura 3 - Slot Dimension Detail

The output, evaluated from input parameters by an analytical calculation, is mathematically defined as a function of $\vec{x}$:

$$\vec{y} = (f(\vec{x})) \qquad (1)$$

For the optimization, it is proposed to apply the method MOGAII, a variation of Multi-Objective Genetic Algorithm MOGA with a directional crossover operator and multisearch elitism [3]. And in this work it will implemented through commercial software called mode FRONTIERTM, from Esteco.

GENERATOR'S CHARACTERISTICS AND TOPOLOGY

The synchronous generator, driven by steam turbines and described in this article, is a four poles round rotor, whose stator and rotor package are a compound of thin sheet metal, as showed at Figure 2, stacked in sub-packages separated by cooling channels according to Figure 4 .

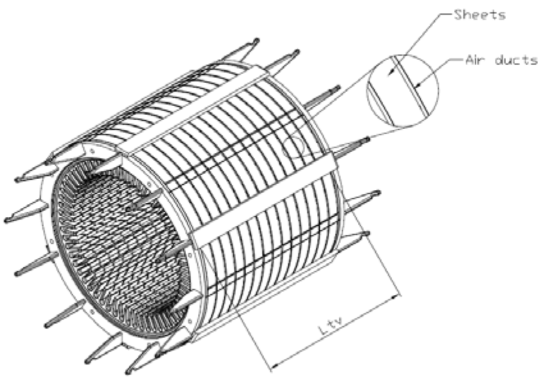

Figura 4 - Pack of Steel Sheets with Air ducts

OBJECTIVE FUNCTION

The formulation of this synchronous generator optimization can be showed as a constrained optimization problem with two objectives:

- Minimization of the yoke induction;
- Minimization of the stator losses.

In compliance with a set of carefully chosen constraints, they provide a fast, indirect and practical way to get a range of solutions that will meet with the objective initially proposed: increasing the generator efficiency.

MODEL

The generator's calculation is implemented through classical equations, according steady state model showed at Figure 6.
Some approximation, such ignoring the low resistance are assumed. The final results will be compared with the WEG industrial calculation, validated through tests with round rotor synchronous machines manufactured for the last 10 years.

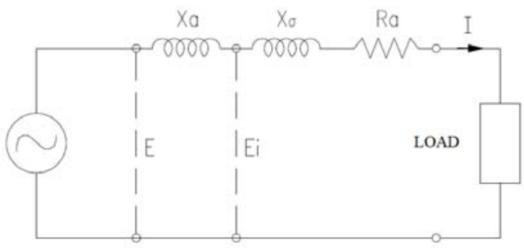

Figura 5 - Steady State Model

Where,
Xa: Armature reactance;
Xσ: Dispersion reactance;
Ra: Armature Resistance.

PARAMETERS AND CONSTRAINTS

The input parameters handled in this paper are summarized in Table 2: The generator geometry, winding and strands are modified in order to reach optimal volume utilization with the maximum efficiency for the frame.
The choice of range of the input parameters is critical to the success of the optimization process as well as for its speed, this way, it is important to establish a strategy that reduces the probability of divergence of the model and provides effective and fast results.
Table 2 shows the values which will be used as input data on generator's optimization.
As placed on the proposition, both the outer stator's diameter, De1, and the stack of sheets, Ltv, are fixed. The same happens to parallel strands of stator in width, Ncpl1, described at Figure 6.

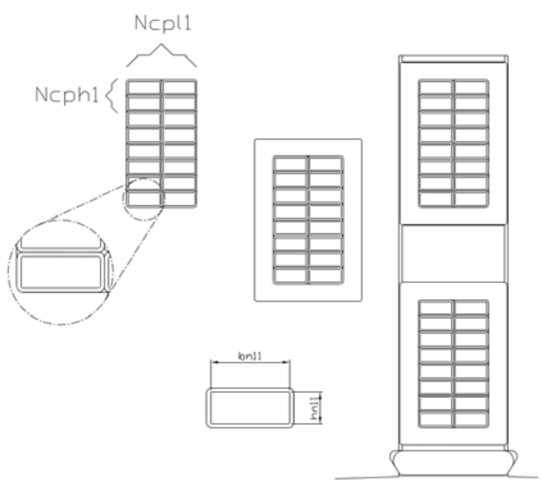

Figura 6 - Schematic Showing the Slot with Winding

With respect to the rotor, except for the outer diameter, all other features have been preserved.

The constraints are defined according to Table 3. They respect some performance boundaries and losses limits, the first one is set by theoretical induction limits, the second one is stated according industrial tests performed at several similar existent generators.

Tabela 2 - Input parameters

Description	Var.	Symbol	Maximum Value	Minimum Value	Unit
Internal Stator Diameter	X_1	Di1	870	850	mm
External Rotor Diameter	X_2	De2	860	830	mm
Parallel Strands of Stator in Height	X_3	Ncph1	2	1	mm
Number of Stator Slots	X_4	N1	84	60	
Number of Turns in Stator Winding	X_5	Z1	11	6	
Stator Strand Width	X_6	bn11	3.55	1.0	mm
Stator Strand Height	X_7	hn1	6.7	4.0	mm
Parallel Path at Armature Winding	X_8	Nph1	2	1	

Tabela 3 - Output parameters and constraints

Description $f(\vec{x})$	Symbol	Max. Limit	Min. Limit	Tolerances	Unit
Short Circuit Ratio	SCR	0.6	0.40	0.05	
Tooth Induction	Bd1	2.2	1.6	0.0	T
Yoke Induction	Bc1	2.0	1.2	0.0	T
Stator Joule Losses	Pj1	50	-	3	kW
Air-gap	δ	-	10.0	0	mm

3. OPTMIZATION TOOL – MODEFRONTIERTM

It is desirable that an optimization tool be adaptable to different practical challenges. This way, there are at least two requirements:

1 It needs to be able to cope with several kinds of software commonly used in an engineering environment.
2 And, related to optimization software, it is important to be flexible, specially related to what type of optimization problem is being treated: single and multi-objective optimization problems, which depend on their employment and goals, must be available.

In this paper, a multi-objective genetic algorithm, MOGA II, available in modeFRONTIERTM tool, is used to optimize a real generator design in a multi-objective problem.
The Figure 7 shows the problem discussed here, assembled on modeFRONTIERTM screen, with the input and output parameters related through a model and all of them integrated in an optimization module.

Tabela 4 - Moga-II - Operator's probabilities

Parameters	
Probability of Direction Crossover	0.5
Probability of Selection	0.05
Probability of Mutation	0.1
Elitism	Enabled

MOGA-II is a version of MOGA from Poloni [4] with elitism. As with any genetic algorithm, this one aims to meet conflicting objectives, guiding the resolution of the problem towards a set of individuals arranged in a Pareto frontier. The efficiency of the MOGA-II is ruled by its operators as well by the use of elitism [5].
The operator's probability used in this paper is according to Table 4.

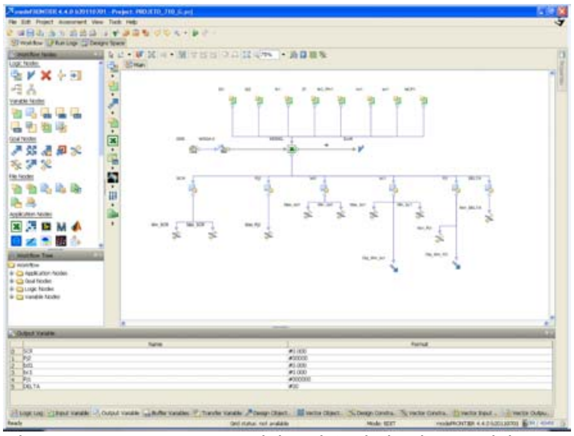

Figura 7 - Parameters, Model and Optimization Module – mode FRONTIERTM Aspect

4. RESULTS AND CONCLUSION

The particular problem developed in this paper is a real world problem, applied to a classical model with few variables. And through this model it is possible to accomplish the primary goal (higher efficiency) proposed in this work, optimizing the four poles generator for a minimum yoke induction and minimum stator losses.

The distribution of the results is showed in the Figure 8: The grey points are the feasible designs and the red ones all the unfeasible designs. There is a large combination of concurrent results, some of them are privileging a minimum stator loss, the other ones the inductions. The final choice is dependent on designer analysis.

The Table 5 presents one of these optimized results, chosen by author to illustrate an interesting option, which, at first sight, does not seem to be a good one.

Comparing it to the original one it is possible to see, just a slight lower induction and a rise of losses. However, there is a good improvement of efficiency (0.3 perceptual points) and a higher SCR, a highly desirable parameter, required by several grid codes with values above the advised by standards, like IEC.

Tabela 5 - Comparative results

Symbol	Description	Original Generator	Optimized Generator	Unit	Diff.
Generator's Topology					
De1	Stator External Diameter	1250	1250	mm	-
Di1	Stator Internal Diameter	850	858	mm	-
De2	Rotor External Diameter	830	832	mm	-
Ltv	Package length	1095	1095	mm	-
N1	Number of Slots	60	72	-	+20%
bn11	Stator Strand Width	6.7	5.6	mm	-
hn1	Stator Strand Height	2.24	2.8	mm	-
Z1	Number of Turns per Slot per parallel path	4.5	4		-13%
δ	Airgap	10	13	mm	+30%
br1	Stator Slot Width	21.7	19.2	mm	-
hr1	Stator Slot Height	86.4	84.4	mm	-
Performance Data					
If	Field Current	189	199.4	A	+5.5%
Bd	Tooth Induction	1.78	1.72	T	-3.5%
ks	Saturation Factor	0.21	0.13		-62%
Pj2	Rotor Joule Losses	43	48	kW	+11%
SCR	Short Circuit Ratio	0.51	0.57		+12%
Objectives					
Bc	Yoke Induction	1.88	1.86	T	-1%
Pj1	Stator Joule Losses	47	49	kW	+4.2%
Main Goal					
η	Efficiency	96.3	96.6	%	-
Pt	Total Losses	232	213	kW	-9%

The reduction of 9% of total losses is specially due to the iron losses. An unexpected association between air gap increase and the induction decrease lessens the saturation of the magnetic circuit (represented at Table 6 by the saturation factor) and thus the iron losses.

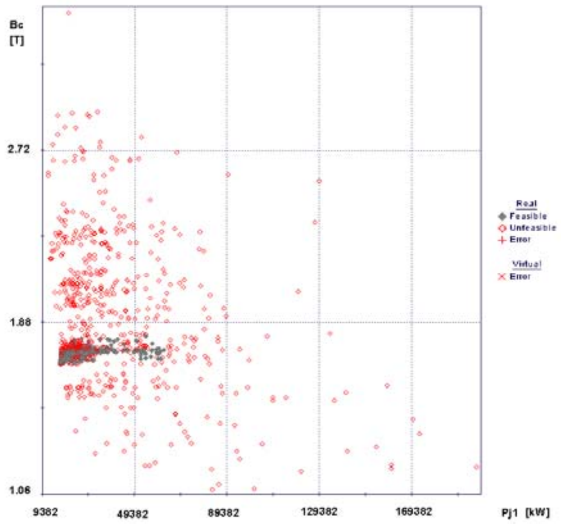

Figura 8 - Optimization Results

- Even being the electrical design a small part of the improvement possibilities of the turbogenerator's efficiency, it was possible , for this generator discussed in this paper, to save 19 kW of total losses, employing an optimization tool.
- It is not necessary enlarging the turbogenerator to achieve a better efficiency, and thus it is possible to keep its cost.

This is just a sample of what can be done using an optimizing tool in an electrical design of turbogenerator. The employment of genetic algorithm in models more sophisticated can probably provide more improvements and economy, and shall be exploited in future studies.

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