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A Genetic Algorithm Solution for Optimization of the Power Generation Potential in Hydroelectric Plants

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***Abstract*—This paper presents an optimization model of the power generation potential for either new or repowered hydroelectric plants. It is based on curves that represent the unit efficiency as a function of the nominal output. The objective is to choose the combination of efficiency curve types that maximizes the power generation for certain load levels. The mathematical formulation results in a mixed integer, nonlinear programming problem. Genetic Algorithm is employed to solve this. The operators and parameters of the model are chosen by simulation using the objective function values as a selection method. A case study is carried out for two Brazilian hydroelectric plants: Sobradinho and Ilha Solteira. The results show the importance of the turbines model choice in order to get the maximum benefit of a plant.**

Keywords—genetic algorithm; turbines; hydroelectric power plants; efficiency curves.

I. Introduction

The Brazilian system of power generation is predominantly hydroelectric. According to [1], despite the incentive to use alternative energy sources, the hydroelectric plants will remain, for many years, the main source of electricity in the country.

For Brazil, [2] predicts an increase of electricity consumption with an annual rate of 3.5% and 5.1% to low and high growth scenarios, respectively. To meet growing demand, there is a need to increase the energy supply through the installation of new plants, including hydroelectric power plants (HPPs).

Another option that may contribute to meet growing demand is to repower the existing plants. The replacement of turbines is necessary because over time a generating unit (GU) suffers a series of thermal, electrical and mechanical stresses in nature. They gradually lose the ability to withstand these stresses and are forced to stop for repairs and maintenance.

More than 50% of Brazilian hydroelectric plants have been in operation for over 20 years. The natural aging process of the units is inevitable. Normal wear and tear includes pitting from cavitation, fatigue cracking, and abrasion from suspended solids in the water. Consequently, after some years the units' performance may decrease [3].

According to [4], the efficiency of the GUs is the main factor that affects the performance of power generation in HPPs. Therefore, it is important to choose appropriate turbines, either in the construction or repowering of HPPs.

This paper proposes to address the following questions:

• Is an advantageous option to choose different types of turbines for a same HPP?

• Which types of turbine efficiency curves would be ideal for each operation system?

These questions are the motivation factors of this paper, that aims to choose combinations of efficiency curves types to ensure maximum generation efficiency, for certain loading regimes. This is a mixed integer nonlinear optimization problem and it has been solved using genetic algorithms (GAs).

This paper is organized as follows. Section II provides the information about types of turbine efficiency curves to optimize the power generation potential. Section III presents the mathematical formulation of the problem. Section IV describes the genetic algorithm features used in this piece of work. Section V shows the information of the case studies. Results are demonstrated in Section VI. Finally, the paper is concluded in Section VII.

II. Turbines Characteristic

The most common turbines are Francis, Propeller, Kaplan and Pelton. Their main characteristics are presented in Table I. The choice of the turbine is determined by rotational speed or specific speed of the turbine. The Francis turbine is the oldest, comprising of a rotational speed between 50 and 500 rpm [5] and head between 20 and 900 m [6]. The Propeller covers heads between 5 and 80 m [7] and a rotational speed between 200 and 1000 rpm [8]. The rotational speed of the Kaplan turbine reaches between 500 and 1000 rpm and, head between

6 and 70 m. Pelton provides a rotational speed between 4 and 70 rpm and heads between 100 and 1770 m [5] [6].

TABLE I. MAIN CHACRACTERISTICS OF THE MOST COMMON TURBINES

Turbine	Rotational speed (rpm)	Head (m)
Francis	50-500	20-900
Propeller	200-1000	5-80
Kaplan	500-1000	6-70
Pelton	4-70	100-1770

For construction or repowering of HPPs, one can choose what type of turbine is ideal, mainly due to the head and rotational speed. Each turbine has a different efficiency curve type, as shown in Fig. 1.

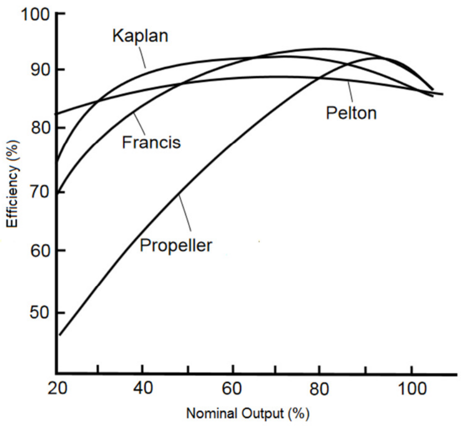

Fig. 1. Efficiency curves of the most known turbines.

As shown in Figure 1, the curves of the Kaplan and Pelton turbines are flatter than Francis and Propeller. [9] defines the efficiency curves of the Kaplan, Pelton, Propoeller and Francis turbines as: flat curve, hook curve and intermediary curve, respectively.

In a HPP the GUs have different goals. For example, some of them may operate on this basis, while others have to follow the load variations, especially in rush hours.

In this paper three load levels are considered: light, intermediate and heavy. The load levels aim to represent the average load and the permanence time of each load. Choosing an adequate curve type only in relation to heavy loads can compromise the efficiency in the generation of light load and vice versa.

It is important to choose efficiency curve types that consider an adequate balance between load and permanence time. Moreover, the operative constraints of the HPP and its GUs must be taken into account, for example: the power balance in each load level and the forbidden zones of operation.

III. MATHEMATICAL FORMULATION

The present problem aims to optimize the efficiency in the generation of electric energy choosing combinations of efficiency curve types. The main elements of the mathematical formulation are the efficiency curve types in function of the generation of the GU. The problem is formulated as follows.

$$Max \quad \frac{\sum_t P^t H^t D^t}{\sum_t P^t H^t \sum_j \sum_k \frac{y_j^{t,k} g_j^t}{\eta^k (g_j^t)}} \tag{1}$$

$$s.t. \quad \sum_j \sum_k y_j^{t,k} g_j^t = D^t \tag{2}$$

$$\sum_k y_j^{t,k} \underline{G}^k \le g_j^t \le \sum_k y_j^{t,k} \overline{G}^k \tag{3}$$

$$y_j^{t,k} \le z_j^k \tag{4}$$

$$\sum_k z_j^k = 1 \tag{5}$$

$$y_j^{t,k}, \; z_j^k \in \{0,1\} \tag{6}$$

for $j = \{1, \dots, J\}$, $t = \{1, \dots, T\}$ and $k = \{1, \dots, K\}$, where:

j	Generating unit index
k	Efficiency curves type index
t	Load level index
$\eta^k(g_j^t)$	Efficiency curve k as function of g_j^t
$\underline{G}^k$	Generation lower limit for GU type k when dispatched (MW)
$\overline{G}^k$	Generation upper limit for GU type k when dispatched (MW)
H^t	Number of hours of permanence in the load level t (h)
P^t	Energy price in the load level t (US$)
D^t	HPP demand in the load level t (MW)
g_j^t	Power generated by the GU j in the load level t (MW)
z_j^k	Indicates if the GU j has efficiency curve type k
$y_j^{t,k}$	Indicates if the GU j with efficiency curve type k is dispatched in the load level t

The objective function (Equation 1) represents the total efficiency in the generation of the HPP. It considers the t load levels, weighted by the number of hours of permanence H^t and energy prices P^t for each load level.

Analyzing the numerator of the objective function, we have that the energy generated at the load level t is $H^t D^t$. The denominator $y_j^{t,k} g_j^t / \eta^k(g_j^t)$ represents the gross output used by the GU j to generate the power g_j^t. The gross output used by HPP to generate D^t is given by the sum for all GUs.

Multiplying the gross output by number of hours of permanence in the load level H^t has the sum in energy. The variable $y_j^{t,k}$ was inserted because it is added generation of a GU considering all the efficiency curve type k. Finally, each load level is weighed for the energy price P^t.

In Equation 2, for each load level, the total demand D^t is equal to the addition of the generation g_j^t of each GU multiplied by dispatch variable $y_j^{t,k}$.

Equation 3 represents the generation limits. These limits are changed as the lower limit given by the minimum generation of one GU in operation. On the other hand, the upper limit is given by the maximum generation of all available units in operation.

According to Equation 4, if the GU has the efficiency curve type k ($z_j^k = 1$), the variable $y_j^{t,k}$ can assume the values "0" or "1". The Equation 5 represents the choice of the efficiency curve type. Each GU can only have one efficiency curve type.

The formulation considers three types of variables: the generation g and two boolean variables. The Equation 6 represents these boolean variables: y that indicates whether or not the GU is dispatched at a determined load level and z reflects the choice of the efficiency curve type.

IV. Genetic Algorithm

Math and computational techniques have been developed for decades with the principles of Darwin's evolution theory, defining what is known as Evolutionary Computation (EC). In this study area, GA is the most used [10].

GAs was developed by [11] who analyzed the phenomena of the process of natural selection of species and the genetic selection of races. Each individual in the GA is the encoding of a possible solution to the problem. This encoding can be binary or real.

The first step towards its implementation is the generation of an initial population that for most problems is generated at random. However, depending on the application forms, the individuals can be selected heuristically to compose a more favorable population [12].

GAs use some genetic operators like crossover and mutation, which are applied to generate new solutions inside a feasible set of solutions. Also, the operators are randomized to provide diversities in the overall population seeking global optimal solutions.

As already stated, the GA is inspired by the mechanism of natural selection and each individual is a possible solution to the problem. According [12], the chromosome is a data structure that represents a possible solution of the optimization problem. Each chromosome is composed of strings of genes and these are composed of alleles. They are the ones that give value to the genes [13]. Depending on the type of problem, it is possible to manipulate the variable of the chromosome.

This section describes the methodology of GA applied to the problem. As it is seen in sequence, the individuals in this approach have real and integer variables. For the real variables we proposed four operators of crossover and four operators of mutation. While to the integer variables we proposed four operators of crossover and two operators of mutation. In addition, four different types were proposed for selection. All these operators were used in the simulations for choice of the best combination among them.

A. Variables representation

In genetic algorithms the variable that characterizes an individual are represented in an order list called string. For this problem, each solution or individual is denoted as follows:

$$I = [\ \underbrace{k_1 \cdots k_J}_{\substack{\text{Efficiency} \\ \text{curve type of GU}}}\ \vdots\ \underbrace{g_1^1 \cdots g_J^1}_{\substack{\text{Chromosome} \\ \text{generation at} \\ \text{load level 1}}}\ \vdots \cdots \vdots\ \underbrace{g_1^T \cdots g_J^T}_{\substack{\text{Chromosome} \\ \text{generation at} \\ \text{load level } T}}\ ]$$

The first chromosome relates to the choice of the efficiency curve type of the GU, represented by integer variables. Each of the other chromosomes, the second until $(T+1)^{th}$ refers to the generation of GUs in a load level, represented by real variables.

An example of a possible individual is shown in sequence:

$$I = [\ 2\ \ 1\ \ 2\ \ 3\ \vdots\ 139\ \ 148\ \ 138\ \ 143\ \vdots\ 160\ \ 136\ \ 0\ \ 0\ ]$$

The sample individual has four GUs, two load levels and three efficiency curve types. GUs 1 and 3 were chosen with efficiency curve type 2; the GUs of number 2 with the efficiency curve type 1 and GU 4 with efficiency curve type 3. The load levels are the 568 and 296 MW, so that the sum of the genes in the second and third chromosomes must be equal to 568 and 296 MW, respectively. In the load level 2, two GUs were not dispatched.

B. Initial Population

1) Integer chromosome: For the first chromosome of the individual, the choice of the efficiency curve type for each GU is made randomly. If there are K differenance efficiency curves types, for each gene of the integer chromosome, there is chosen a number randomly between 1 and K, called k_J.

2) Real chromosome: Because of the constraints of load demand and prohibited zones, each chromosome is treated separately. As well as crossover and mutation operators, which are applied to the chromosomes, separately, and not as an individual, but as a whole.

For the creation of a real chromosome of an individual, values 0 or 1 are generated randomly. With this in mind, it is determined which GUs will not be dispatched (0) or will be dispatched (1). The latter have a generation allocated to them. Two positions that have this generation allocated are randomly chosen and the unit whose load will be increased or decreased is also chosen randomly. For example, if the combination of GU is

$$I = [\ 0\ \ 1\ \ 0\ \ 1\ \ 1\ \ 1\ ]$$

i.e., units 2, 4, 5 and 6 are chosen to be dispatched.

Thus, for $D^t = 280$ MW, an individual in the initial population would be

$$I = \left[0 \quad \frac{280}{4} \quad 0 \quad \frac{280}{4} \quad \frac{280}{4} \quad \frac{280}{4} \right]$$

i.e.,

$$I = [\,0 \quad g_2^t \quad 0 \quad g_4^t \quad g_5^t \quad g_6^t \,]$$

Two positions are randomly chosen (e.g., 2 and 6) and the unit whose load will be increased or decreased is also chosen randomly. So, the power in unit 2 will be increased and the power in unit 6 will be decreased.

A number a between 0 and $max\{a_1, a_2\}$ is randomly generated and the individual changed to

$$I = [\,0 \ \{g_2^t + a\,\}\, 0 \ \ g_4^t \ \ g_5^t \ \ \{g_6^t - a\}\,],$$

where $a_1 = \left\{\overline{G}^k - g_2^t\right\}$ and $a_2 = \left\{\, g_6^t - \underline{G}^k\right\}$.

The same procedure is carried out for the other pairs. This causes the sum of the input generation of individuals not changing, just as the generation limits. This procedure means that the initial population contains individual diversity.

A. *Selection, Crossover and Mutation*

Table II shows all operators used in the case studies. The selection processes used were: Roulette Wheel, Tourrnament, Ranking and Elitism with Random. Three crossover operators were adopted, that the exchange of GUs were developed particularly for the considered problem. They are: One-point, Two-point and Arithmetic.

Four mutations were proposed for real chromosomes and two for the integer chromosomes. Adaptations were made to some operators found in the literature.

TABLE II. SELECTION, CROSSOVER AND MUTATION OPERATORS

Selection	**Crossover**	**Mutation for real chromosomes**	**Mutation for integer chromosomes**
Roulette Wheel	One-point	Gaussian	Integer
Tourrnament	Two-point	Inversion	Inversion
Ranking	Arithmetic	Inversion 0-1	-
Elitism with Random	-	Gaussian with Inversion 0-1	-

V. CASE STUDY

For this problem, the case study is constituted of the demand factor, electric energy price and the Sobradinho and Ilha Solteira HPPs data. The data was provided by three companies: *Trade Agency (*CCEE), *Companhia Hidro Elétrica do São Francisco* (CHESF) and *Companhia Energética de São Paulo* (CESP).

CCEE supplied the energy spot price, load duration curve of generation and load levels. CHESF and CESP provided data such as: efficiency curves of HPPs, generation limits of GUs and load duration curve.

A. *Demand factor – CCEE*

The Brazilian interconnected system has 4 subsystems. Each subsystem has factors that refer to its average demand. Table III presents data related to the Northeast (NE) and Southeast (SE) subsystems in which Sobradinho and Ilha Solteira HPPs are respectively located. In this table, two sets of data are presented: demand factors and percentages of duration in the load levels: heavy, intermediate and light.

TABLE III. DEMAND FACTORS AND PERCENTAGES OF DURATION PER LOAD LEVEL AND SUBSYSTEM

Year 2010	**Northeast subsystem**		
	Heavy	***Intermediate***	***Light***
Demand factor	1.16	1.04	0.89
Hours of permanence (%)	10.34	51.87	37.79
	Southeast subsystem		
Demand factor	1.20	1.08	0.84
Hours of permanence (%)	10.34	51.87	37.79

B. *Electric energy spot price – CCEE*

It was considered the average energy price per month, per load level and per subsystem, of the year 2009. Table IV shows the price.

TABLE IV. ENERGY SPOT PRICE PER LOAD LEVEL

Year 2009	**Northeast subsystem**		
	Heavy	***Intermediate***	***Light***
Price (US$/MWh) [a]	65.30	64.88	64.66
	Southeast subsystem		
Price (US$/MWh) [a]	80.34	78.84	76.02

[a] Considering an exchange rate of 1.997 US$/R$

C. *Sobradinho HPP*

1) Efficiency curves: Sobradinho HPP has six GUs with Kaplan turbines. For the case study, the efficiency curve types are hypothetical. It was considered three different efficiency curve types (Fig. 2). Type 1 represents a typical Kaplan curve. Types 2 and 3, more pronounced, resemble Propeller turbines curves.

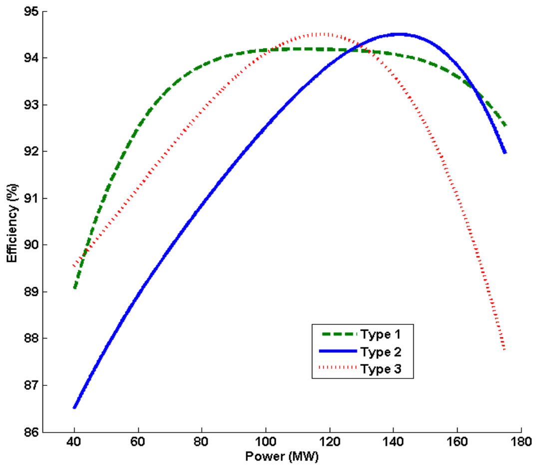

Fig. 2. Efficiency curve types used for the implementation of Sobradinho.

2) Load duration curve: Load duration curve is profile of system demand that can be drawn for specified periods of time (e.g., daily, monthly and yearly). This curve illustrates the variation of a certain load such that, the greatest load is plotted on the left and the smallest one on the right, as seen in Fig. 3. This figure represents load duration curve Sobradinho HPP for one day divided into three load levels.

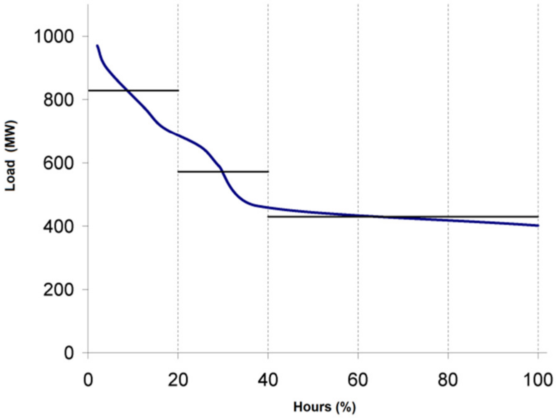

Fig. 3. Load Duration Curve for one day of Sobradinho HPP.

3) Scenario HPP Sobradinho: For Sobradinho HPP simulation, it was created the scenario shown in Table V. From then on, we used the factors that refers to the Northeast subsystem: 1.16; 1.04 and 0.89 for heavy, intermediate and light load levels, respectively.

These values are the averages of the factors for all the year of 2010. Thus, the load levels are 928, 832 and 712 MW. For the time of duration in each load level, 10.34% of the time refers to the heavy load level, 51.87% to intermediate and 37.79% to the light, for year 2010. The energy prices refer to 2009. The average price in that year was US$ 69.49; US$ 68.81 and US$ 66.79 per MWh for the heavy, intermediate and light load levels, respectively.

TABLE V. SCENARIO SOBRADINHO HPP

Year 2010	**Sobradinho HPP**		
	Heavy	***Intermediate***	***Light***
Load (MW)	928	832	712
Hours of permanence (%)	10.34	51.87	37.79
Price (US$/MWh)	69.49	68.81	66.79

D. Ilha Solteira HPP

1) Efficiency curves: Ilha Solteira HPP has twenty GUs with Francis turbines. Their efficiency curves are divided into two types. The curve type 1 is composed for the GUs of 1 to the 4, with a peak between 120 and 130 MW. The curve type 2 refers to the other GUs with a peak between 130 and 140 MW. Fig. 4 shows these curves.

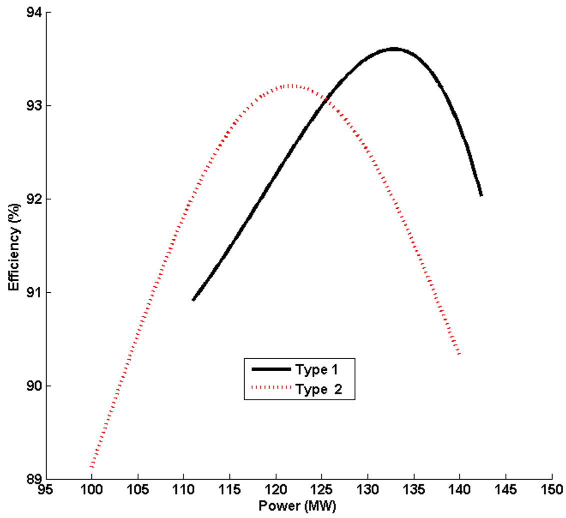

Fig. 4. Efficiency curve types used for the implementation of Ilha Solteira HPP.

2) Load duration curve: This Fig. 5 represents load duration curve Ilha Solteira HPP for one day divided into three load levels.

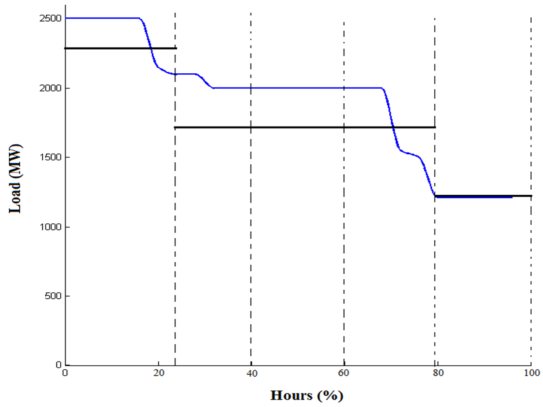

Fig. 5. Load Duration Curve for one day of Ilha Solteira HPP.

3) Scenario Ilha Solteira HPP: For Ilha Solteira HPP simulation, it was created the scenario shown in Table VI. From then on, we used the factors that refers to the Southeast subsystem: 1.20; 1.08 and 0.84 for heavy, intermediate and light load levels, respectively. These values are the averages of the factors for all the year of 2010.

Thus, the load levels are 2040, 1836 and 1428 MW. For the time of duration in each load level, 10.34% of the time refers to the heavy load level, 51.87% to intermediate and 37.79% to the light, for year 2010. For this case study, energy prices were not considered.

TABLE VI. SCENARIO HPP ILHA SOLTEIRA

Year 2010	Ilha Solteira HPP		
	Heavy	***Intermediate***	***Light***
Load (MW)	2040	1836	1428
Hours of permanence (%)	10.34	51.87	37.79

VI. RESULTS

A. *Genetic Algorithm parameter settings*

All operators were presented in Section IV. In total there are 128 combinations of operators proposed for solving the problem. In choosing the best combination of parameters, we used load levels obtained from the operating history of the Sobradinho HPP.

Energy prices were considered equal 1, which leads to no weighting price in the objective function. So, in the choice of the best combination parameters, was taken into account just energy efficiency optimization.

Simulations were run with all combinations of the operators proposed. The parameters were fixed in:

- Population size: 50
- Mutation rate: 0.1
- Crossover rate: 0.9
- Iterations: 5000

The algorithm was repeated 50 times for each combination, resulting in the best combinations that are presented in Table VII. The columns in this table identify the operators used, and indicate the values of the functions objective for each combination.

TABLE VII. RESULTS OBTAINED WITH THE COMBINATIONS OF OPERATORS OF GA

Selection	Crossover	Mutation	Mutation Type	Value of the objective function
Roulette Wheel	One point	Inversion	Integer	94.490
Roulette Wheel	One point	Inversion	Inversion	94.490
Roulette Wheel	Two point	Inversion	Integer	94.490
Roulette Wheel	Two point	Inversion	Inversion	94.490
Elitism with Random	Two point	Inversion	Integer	94.491
Ranking	One point	Inversion	Integer	94.491

The values of the objective function were used as a criterion of selection of the best combinations of the operators. After the attainment of the best combinations, the crossover rate and mutation rate were varied in the values shown in Table VIII.

TABLE VIII. CROSSOVER AND MUTATION RATES

Rates	Value				
Mutation	0.001	0.010	0.050	0.100	0.20
Crossover	0.30	0.50	0.75	0.90	1.00

Multiplying the best combinations of operators (Table VII) with the five rates of crossover and mutation (Table VIII), it has 150 combinations of operators and rates. Again, some parameters were fixed, such as: the population size in 50 and the number of iterations in 2500.

The algorithm was repeated 20 times for each of the 150 combinations. The best combination is ranking selection, One point crossover, Inversion mutation and Integer mutation type. The rates were 0.2 for mutation and 0.9 for crossover.

The value of the objective function of the 20 repetitions for the chosen combination is 94.490. The convergence occurred at the average, in 655. Fig. 6 shows the best evaluation found before than 500 iterations.

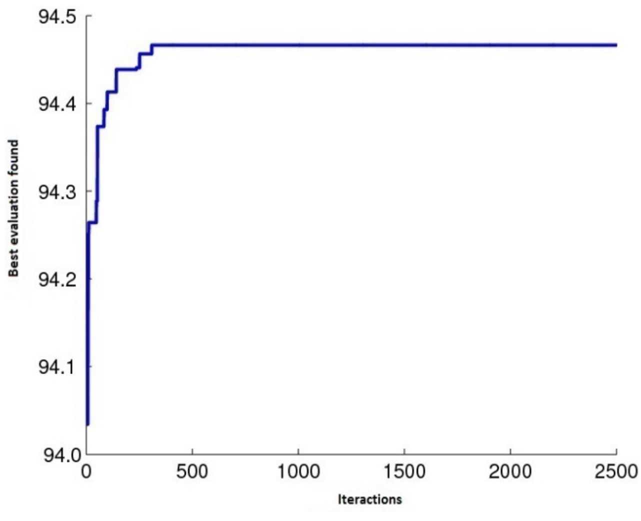

Fig. 6. The best evaluation found before than 500 iterations.

In the best solution, was found, between the repetitions (objective function 94,490), only the efficiency curve type 2 was chosen. The solution is presented in Table IX.

TABLE IX. BEST SOLUTION FOUND FOR PARAMETER SETTINGS

GU	Heavy	Intermediate	Light
1	138.08	142.05	143.79
2	138.08	142.18	0
3	138.08	0	143.16
4	138.08	143.50	0
5	138.08	0	0
6	138.08	143.70	143.06

B. Scenario Sobradinho HPP

For this scenario, the optimal value of the objective function in the simulations with GAs was 94.450, being selected only efficiency curve type 2 i.e., Propeller turbines curves.

The distribution of the allocation of generation presented in Table X. This table shows the range of operation of HPP divided into intervals more than the zero point. It can be noted that in the heavy level, the six GUs have generated between 148 and 162 MW. In the range of 135 to 148 MW has a higher incidence of allocation of generation for the intermediate and light load level. This happens because, as all curves types 2 were chosen, this is the range that has highest values of efficiency.

TABLE X. DISTRIBUTION OF THE ALLOCATION OF GENERATION SOBRADINHO HPP

Range	Heavy	Intermediate	Light	Total
0	-	-	1	1
40 |- 54	-	-	-	-
54 |- 67	-	-	-	-
67 |- 81	-	-	-	-
81 |- 94	-	-	-	-
94 |- 108	-	-	-	-
108 |- 121	-	-	-	-
121 |- 135	-	-	-	-
135 |- 148	-	6	5	11
148 |- 162	6	-	-	6
162 |- 175	-	-	-	-

The best solution found is shown in Table XI. In heavy load level, all the GUs were dispatched in 154.67MW. In the intermediate load level the GUs were dispatched in the interval where the efficiency curve type 2 has higher efficiency, between 135 and 148 MW. In the light load level, a GU 4 was kept stopped.

TABLE XI. BEST SOLUTION FOUND FOR SOBRADINHO HPP

GU	Curve efficiency type	Heavy	Intermediate	Light
1	**2**	***154.67***	***138.45***	***143.28***
2	2	154.67	136.14	141.23
3	2	154.67	140.75	143.28
4	2	154.67	139.34	0
5	2	154.67	137.43	141.52
6	2	154.67	139.90	142.69

The computational time for simulation with GA was 2 minutes for 2500 iterations, proving to be efficient. Thus, according to the results shown, that with this scenario, it is preferable to choose Propeller turbines, since the operation is adequate.

C. Scenario Ilha Solteira HPP

The Table XII shows the best solution for Ilha Solteira HPP, where only three GUs was chosen, efficiency curve type 2, and the other GUs chosen, curve type 1. In this HPP exist 16 GUs with type curve 1 and 4 GUs with type curve 2, so the results show a contrary decision.

TABLE XII. BEST SOLUTION FOUND FOR ILHA SOLTEIRA HPP

GU	Curve efficiency type	Heavy	Intermediate	Light
1	1	137.42	132.07	0
2	1	134.4	135.2	124.15
3	1	135.34	0	131.5
4	2	137.6	125.87	0
5	1	0	135.57	0
6	1	0	128.22	129.22
7	1	136.66	134.07	126.93
8	1	133.24	130.22	134.47
9	1	136.29	134.74	0
10	2	132.32	0	0
11	1	0	0	128.14
12	1	134.58	136.41	120.96
13	1	0	0	0
14	1	137.31	126.76	138.68
15	1	0	0	0
16	2	135.82	127.09	125.16
17	1	135.89	0	0
18	1	139.68	129.53	0
19	1	138.76	127.55	132.7
20	1	134.69	132.76	136.09

Tables XIII and XIV present the distribution of the power generated by each curve type 1 and 2, respectively.

TABLE XIII. DISTRIBUTION OF THE POWER GENERATED CURVE TYPE 1

Range	Heavy	Intermediate	Light	Total
0	5	5	7	17
100 |- 110	-	-	-	-
110 |- 120	-	-	-	-
120 |- 130	-	4	5	9
130 |- 140	12	8	5	25

TABLE XIV. DISTRIBUTION OF THE POWER GENERATED CURVE TYPE 2

Range	Heavy	Intermediate	Light	Total
0	-	1	2	3
100 |- 110	-	-	-	0
110 |- 120	-	-	-	0
120 |- 130	-	2	1	3
130 |- 140	3	-	-	3

The GUs with the efficiency curve type 1 were mostly allocated in the higher power (between 130 and 140 MW). Already GUs with efficiency curve type 2 were distributed over the last two intervals, considering the total for all load levels.

The stopping condition was a fixed number of iterations, in this case 500, and the computational time for simulation was 42 minutes and can be seen in Fig. 7, but the best evaluation found before than 500 iterations.

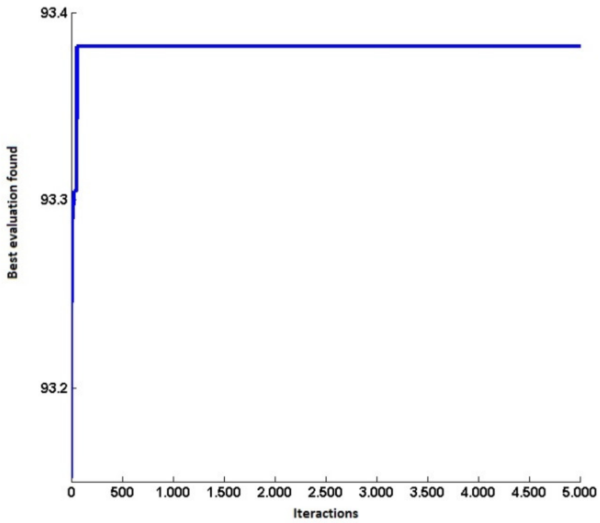

Fig. 7. The best evaluation found before than 500 iterations to Ilha Solteira

VII. CONCLUSION

We proposed a problem related to the optimization of the power generation potential in hydroelectric plants. It deals with the choice of efficiency curve types for the generating units to maximize the efficiency in generation. It's an approach not found in the bibliography. To solve this problem, we used GA which has proved effective, particularly with respect to the computational time. Efficiency curves were used with characteristics of Kaplan and Propeller turbines. The results show that with an appropriate operation, it can be arrived at the lock roads with higher efficiency of turbines Propeller at the Kaplan, and the turbines Propeller has the advantage of a lower cost. This shows, that to install Propeller turbines, it may be advantageous in the aspect of efficiency and economy, as an appropriate operation. Depending on the type of hydroelectric power plant, Propeller turbines can be installed always operating with high efficiency, at the base, and Kaplan turbines making load monitoring and availability of spinning reserve.

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