Computational Model for the Optimization of the Generation of Thermal Power Plants in Brazil

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Abstract. An organized infrastructure and available energy resources are fundamental for the development of a country to be continuous and effective. Although Brazil has many natural resources and a large water structure, other types of energy generation sources are required to contribute to the country's energy demand. Given this, thermoelectric generation has characteristics that make it capable of guaranteeing the necessary complementation, making the reliable system. For this, the planning of the hydrothermal operation is necessary to determine the optimal generation to guarantee the supply with efficiency, safety and economy. Given the complexity of the system, computational models help in decision-making on determining the optimal generation. Therefore, this research work seeks to explore a methodology that aims to determine the optimal generation of thermoelectric plants in part of the Brazilian system, based on the necessary complementation determined by the optimal generation of hydroelectric plants. In this study, the real data from the Brazilian system, available on the NEWAVE deck, were modeling and processed by Linear Optimization Toolbox of MATLAB® program. After the performance of tests, satisfactory results were presented and demonstrated that the proposed methodology is efficient for determining the generation of the thermoelectric system.

Keywords: Thermal Operations Planning; Optimization Algorithm; Numerical Modeling

1 Introduction

The importance of the electricity industry is unquestionable, as it is a vital input that sustains the full functioning of any nation and contributes to economic development and growth. In developing countries, the energy demand increases as the economy grows. For that, it is necessary a system that guarantees the energy supply to society with reliability and adequate costs.

In Brazil, the Nacional Interconnected System is planned and controlled by the National System Operator (NSO). The NSO has a generation system that is divided into four Subsystems: South, Southeast and Midwest, Northeast and North, where the exchange of electricity occurs through the transmission network, as shown in Figure 1 [1].

Thermoelectric plants correspond to 30.1% of the Brazilian electrical matrix. It is represented by the sum of energy sources: natural gas, 12.8%; biomass, 8.2%; coal and derivatives, 3.9%; oil derivatives, 3%; and nuclear energy, 2.2%. The other sources of energy are hydroelectric generation (56.8%), with great representation and dependence on the energy sector; solar and wind generation, which add up to a total of 13.1%, but are not considered in medium-term planning due to their intermittency [2].

The operation planning of hydrothermal systems is intrinsically linked to the decision to use available energy resources. Decision making considers water and thermal availability, that is, the planning of these sources will guarantee the supply of electricity to the system.

Figure 1 – Nacional Interconnected System [1]

For this entire generation and transmission system to be controlled and operated by National System Operator, the Electric Energy Research Center (CEPEL) developed computational models to solve the problem of economic dispatch of the hydrothermal system. NEWAVE is the medium-term planning model (up to 5 years, with monthly discretization) [3].

Currently, NSO works to solve the problem that is associated with the conflict over water use and maintaining the reliability of the system. Faced with a low hydroelectric generation, it resorts to the high costs of thermoelectric plants to supply the load. This operation is very expensive, but it is the available resource that must be used to maintain security in the service.

Operation planning has the same problem as economic dispatch (ED). It is a constrained optimization problem, widely used in power systems. Goals are common when solving an ED problem. The first is to minimize the total cost of generation for all generating units. The second is to satisfy all constraints that the power system contains, as described by JI [4]. Following this definition, the problem must be solved by optimizing the cost of the plant while satisfying the system demand and plant operating constraints.

The economic dispatch determines that thermoelectric plants are optimized in order of merit of lowest cost. This cost must cover the costs of operating the enterprise for each megawatt-hour (MWh) generated by the plant. To obtain this value, the plants add the variable cost of fuel, operation and maintenance, as described by the EPE [5].

When the operation planning includes optimized thermoelectric generation, the tendency is to maintain adequate levels in the reservoirs. In this way, contribute to the minimization of operating costs in the future. Therefore, it is important to avoid thermal dispatch above planned values. To guarantee this, the operation planning must be carried out using a system that supports the best decision to be taken and does not compromise the generation goals.

The Brazilian Electrical System has a natural complexity that demands constant investments in methodologies and computational tools for planning the operation. In this context, this paper contributes to the development of a computational model for the optimization of thermal power generation in Brazil, using real data provided by NSO. The case study carried out in this research encompasses Subsystem 1, which includes the Southeast and Midwest regions of Brazil, where 70% of the reservoirs are located, the thermal generation represent

12,7GW and it is responsible for approximately 60% of the system load.

2 Proposed methodology

2.1 Mathematical Modeling

The algorithm was desenvolved to solve the proposed problem is based on the mathematical model described by WOOD [6]. The objective function of this study, represented by equation 2, aims to minimize the cost of thermoelectric plants described by the equation 1. Subject to a power balance restriction, described by the equation 3, which equals the sum of the generated powers to meeting the requested demand, and the restrictions of minimum and maximum generation of each thermoelectric plant described in equation 4.

$$C(Pg_i) = b_i.Pg_i \tag{1}$$

$$Min \sum_i C(Pg_i) \tag{2}$$

Subject to:

Active Power Balance Constraint:

$$\Sigma\, Pg_i = D \tag{3}$$

Operating Limits Constraint:

$$Pg_{imin} \leq Pg_i \leq Pg_{imax} \tag{4}$$

Where:
i : Thermoelectric plant (unit);
$C(Pg_i)$: Total cost of the operation (R$/h);
b_i : Variable unit cost of the thermoelectric plant (R$/MWh);
Pg_i : Total generation of the thermoelectric plant (MW);
$Pg_{i\mathrm{min}}$: Minimum generation of the thermoelectric plant (MW);
$Pg_{i\mathrm{ma}}$: Maximum generation of the thermoelectric plant (MW);
D : Demand of the system (MW).

The calculation of the Maximum Generation of thermoelectric plants, in NEWAVE, multiplies the power of the plant by its Maximum Capacity Factor and by Forced and Scheduled Unavailability Equivalent Rates, as described in technical note 49 of CEPEL [7]. The formulation is described in Equation 5.

$$Pg_{imax} = P_i.\left(\frac{FCMX_i}{100}\right).\left[1-\left(\frac{TEI\ \ _i}{100}\right)\right].\left[1-\left(\frac{IP_i}{100}\right)\right] \tag{5}$$

Where:
$Pg_{i\mathrm{max}}$: Maximum generation of the thermoelectric plant i (MW);
P_i : Effective power of the thermoelectric plant i (MW);
$FCMX_i$: Maximum Capacity Factor of the thermoelectric plant i (%);
$TEIF_i$: Forced Unavailability Equivalent Rate of the thermoelectric plant i (%);
IP_i : Scheduled Unavailability Equivalent Rate of the thermoelectric plant i (%).

2.2 Developed Algorithm

The algorithm was desenvolved as described in the flowchart in Figure 2 and simulated on a notebook with an i7 processor. The simulation was performed for a period of 12 months and converged to a time of less than one minute.

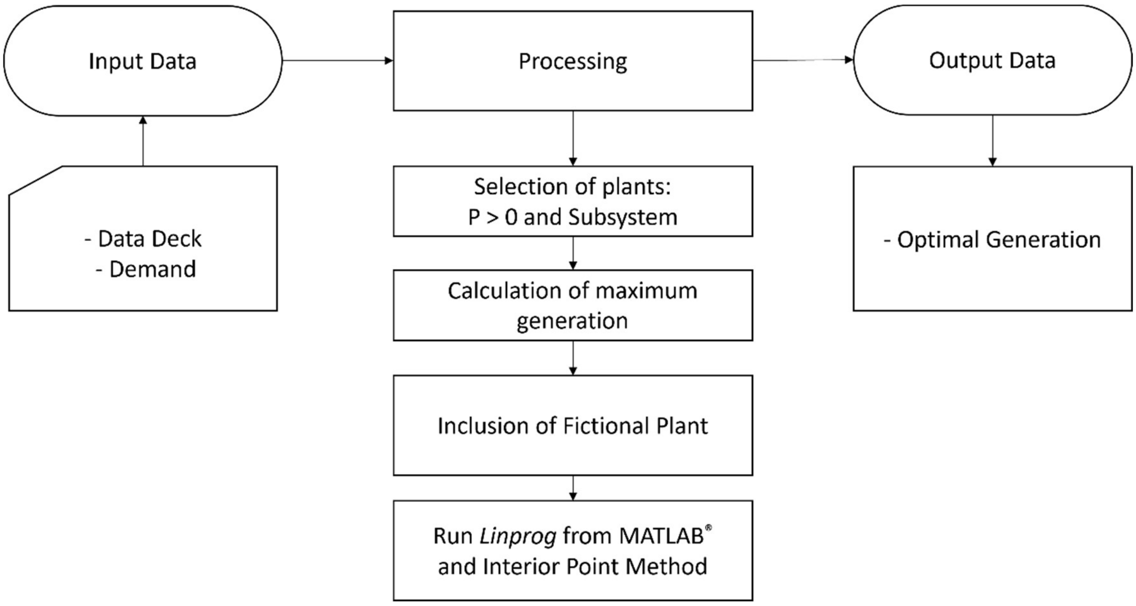

Figure 2 – Algorithm Flowchart

First, the algorithm reads the input data that are the real data of thermoelectric plant of the Brazilian National Interconnected System, the files are available in the Price Deck of the CCCE website [10], and demand, data is available on the Energ.IA Platform, at the Laboratory of Technology and Bioinspired Solutions (LabBITS) at UFABC [11].

The price Deck files used in this work are: *term.dat*, *conft.dat* and *clast.dat*. In the *term.dat* file, the power, Maximum Capacity Factor, Forced Unavailability Equivalent Rate, Scheduled Unavailability and Minimum Thermal Generation data are read by the algorithm to calculate the maximum generation of each plant, which is the maximum limit of the operating restriction, as described in Equation 5. In the *conft.dat* file, the algorithm reads the subsystem and the plant name. And from the *clast.dat* file, the algorithm reads the fuel and cost.

The Platform Energ.IA also processes data from the price deck and, as a result, informs whether or not there is a need for thermoelectric complementation. This program is based on Genetic Algorithm and otimized the generation of hydroelectric plants and was developed by LEITE [12].

During processing, data are filtered to select existing plants with power greater than zero and by subsystem. Then, it was necessary to add Equation 5 in the algorithm for calculating the maximum generation per plant, in order to meet the maximum limit of the operating restriction of the plants.

Due to the maximum generation of all plants being lower than the thermal complementation for Subsystem 1, there was a need to include Fictional Plant with high cost. The cost was higher in relation to the others, so that this plant was last in the list in order of merit. As for the other parameters of this plant, were determined values based on the other plants according to the maximum power, the minimum of the minimum thermal generation, the average of the Maximum Capacity Factor, Forced Unavailability Equivalent Rate and Scheduled Unavailability Equivalent Rate values, and ten percent more for the highest value of the unitary variable cost.

Finally, the data were processed by the algorithm. The algorithm was based on the linear programming technique, due to this, *linprog* is ideal for solving the problem. *Linprog* is available in the MATLAB® optimization toolbox. This tool allows specifying a linear objective function, as well as the constraints of the problem, in the form of linear inequalities or equalities. *Linprog's* syntax is represented by Equation 6.

$$[x, fval] = linprog(f, Aeq, beq, lb, ub) \tag{6}$$

Where:
f : vector of the coefficient of the objective function;
Aeq : matrix of equality constraints;
beq : vector of equality constraints;
lb : vector of the lower limit of the decision variable;
ub : vector of the maximum limit of the decision variable;
x : vector of the objective function decision variable;
$fval$: objective function value.

Linear programming (LP) is a mathematical optimization method that was developed by George Dantzig around 1940 [8]. This technique is applied to problems involving linear functions, subject to a set of linear constraints. Based on this concept, the algorithm was desenvolved used this technique and applied in this study.

In addition, can be chosen the resolution method. In this paper was used the method of interior points. The interior point method was originally developed to solve LP problems and is faster than the conventional simplex algorithm in linear programming [9]. This method which uses the same standard way as linprog for troubleshooting. It is described as a method that does not store or operate on complete matrices, so it uses low memory and has the ability to solve large problems quickly.

Thermal complementation was included in the vector of equality constraints (beq), as monthly demand input data, for a period of 12 months. With the reading of the real data of the 43 UTEs in the equality restriction matrix (Aeq), and also considering the operative limits (lb and ub), which add up to 89 restrictions. The sum of these parameters makes the optimization complex due to its large dimension.

The output data, which are the plants dispatched in order of merit with the respective fuels and costs, result in the monthly optimal generation.

3 Case Study

For the case study, the algorithm was configured to filter the plants belonging to Subsystem 1, which represents the states of the Southeast and Midwest (SE/CO). From these data were executed some tests to prove the convergence of the proposed algorithm. From that, can be present the output data of the algorithm. The Table 1 only show the results to month 6, but the same was executed for the others months.

The maximum generation of Subsystem 1, calculated by the algorithm, is 10,730.08 MW (sum of the maximum generation until Xavantes Plant, in column 5), as described in the table 1. The maximum thermal complementation is 11,150.24 MW for month 6, in column 7. In this scenario, the algorithm did not converge due to the constraint of the demand, as described in Equation 3. Convergence occurs when Fictional Plant is included, adding the generation required to completed the load.

In Figure 3 are all 44 plants (including the Fictional Plant) selected by the algorithm per merit order of lowest cost. Fictional Plant was included in the algorithm with the highest cost, so that the system uses this plant as the last option and not used as a priority over the others when optimizing in merit order. The cost of last plant is considered the marginal operating cost, which is the cost of produce the next megawatt-hour (MWh).

Therefore, these data are the result of the proposed optimization to determine the optimal generation of the simulated Thermoelectric plant in merit order, which result in the monthly optimal generation for the 12-month period.

Table 1. Output Data for Month 6

Name	Cost (R$/MWh)	Fuel	Power (MW)	Maximum generation (MW)	Minimum generation (MW)	Month 6 (MW)
CUIABA G CC	0	Gas	529	469.83	0	469.83
DAIA	0	Diesel	44	37.16	0	37.16
DO ATLAN_CSA	0	Process Gas	255	226.56	223.78	226.56
PREDILECTA	0	Biomass	5	4.69	0	4.69
T. NORTE 1	0	Diesel	64	60.76	0	60.76
W. ARJONA	0	Gas	177	164.57	0	164.57
ANGRA 2	20.12	Nuclear	1,350	1,176.82	1,080.00	1,176.82
ANGRA 1	31.17	Nuclear	640	558.02	509.82	558.02
STA VITORIA	90.00	Biomass	41	30.50	12.46	30.50
ONCA PINTADA	94.43	Biomass	50	43.79	0	43.79
BAIXADA FLU	100.63	Gas	530	426.11	0	426.11
NORTEFLU-1	109.65	Gas	400	400.00	399.99	400.00
NORTEFLU-2	125.89	Gas	100	89.16	0	89.16
DO ATLANTICO	230.67	Process Gas	235	208.79	201.5	208.79
GNA I	238.20	Gas	1,338	1,256.84	0	1,256.84
NORTEFLU-3	243.49	Gas	200	178.32	0	178.32
ST. CRUZ 34	310.41	Oil	436	249.13	0	249.13
TRES LAGOAS	319.35	Gas	350	270.33	0	270.33
IBIRITE	346.37	Gas	235	202.08	0	202.08
TERMORIO	381.75	Gas	989	772.99	0	772.99
CUBATAO	400.43	Gas	216	185.27	0	185.27
ST. CRUZ NOVA	430.14	LNG	500	424.44	0	424.44
SEROPEDICA	469.39	Gas	360	266.33	0	266.33
PIRAT.12 G	470.34	Gas	200	164.29	0	164.29
JUIZ DE FORA	522.96	Gas	87	79.05	0	79.05
KARKEY 013	531.09	Gas	243	233.35	0	233.35
KARKEY 019	531.09	Gas	116	111.39	0	111.39
PORSUD I	632.43	Gas	110	105.63	0	105.63
PORSUD II	634.94	Gas	72	69.14	0	69.14
N. PIRATININGA	654.42	Gas	479	327.01	0	327.01
LINHARES	668.68	LNG	204	195.52	0	195.52
LINHARES PCS	750.00	Gas	36	34.57	0	34.57
PAULINIA VER	750.00	Gas	16	15.79	0	15.79
POVOACAO 1	750.00	Gas	75	72.03	0	72.03
VIANA 1	750.00	Gas	37	35.53	0	35.53
NORTEFLU-4	778.95	Gas	127	113.24	0	113.24
TERMOMACAE	886.91	Gas	929	783.40	0	783.40
T. NORTE 2	910.86	Oil	349	322.69	0	322.69
R. SILVEIRA	978.10	Gas	25	16.31	0	16.31
VIANA	1,265.03	Oil	175	172.05	0	172.05
GOIANIA II	1,933.06	Diesel	140	79.50	0	79.50
PALMEIRAS GO	2,250.47	Diesel	176	43.34	0	43.34
XAVANTES	2,639.40	Diesel	54	53.75	0	53.75
		TOTAL		10,730.08	-	-
FICTIONAL PLANT	2,903.34	Undefined	1,350	1,147.54	0	420.16
		TOTAL		11,877.62	-	11,150.24

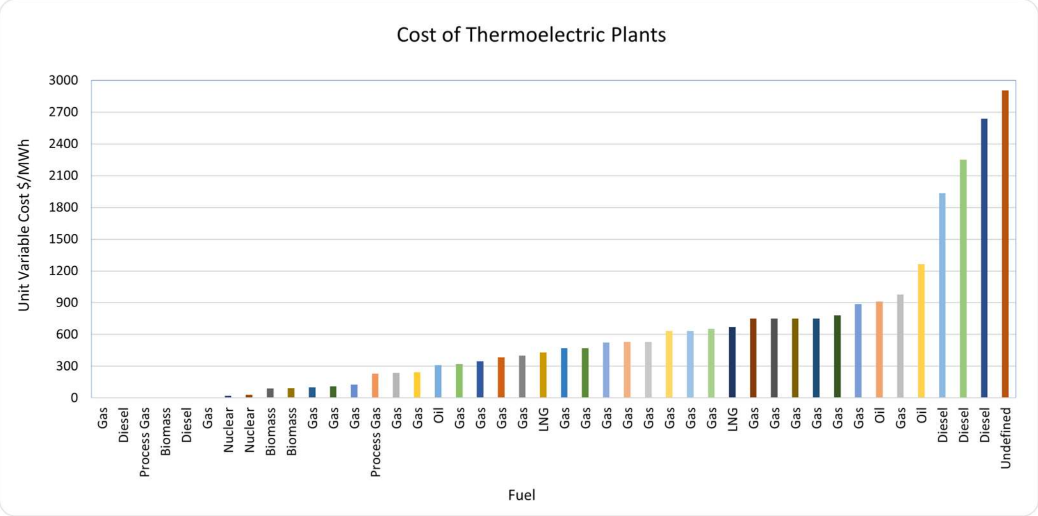

Figure 3 - Unitary Variable Cost per Fuel

4 Conclusions

Based on the monthly thermal complementation data and real data from the thermoelectric plant, the solution to the problem was found through optimization by order of merit of lowest cost. Thus, resulting in the optimal generation for the 12-month period. In the case study, the values demonstrated the convergence of the algorithm. Thus, the results confirm the proposed methodology. Therefore, this demonstrates that the results obtained can contribute to decision making and the proposed methodology can be implemented on the Energ.IA platform.

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