Structured Model for Hydrothermal System Operation and Optimization

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Abstract. This paper presents an analysis for optimizing hydrothermal system operation within the Brazilian energy sector.

In the last years, researchers at the Laboratory of Bio-Inspired Technologies and Solutions from Federal University of ABC (LabBITS - UFABC) have been implementing a platform for accessing the information of the Brazilian electric power generation system from a SQL (Structured Query Language) database, regularly updated from the ONS's provided package of files. The database is accessed by the laboratory researchers via a REST (Representational State Transfer) API (Application Programming Interface) which is used to supply the researchers with the parameters of the energy system models used in the energy operation planning calculations.

In 2024, utilizing Java object models for hydroelectric power plants, a structured approach was developed, organizing plants into power plant systems to capture the interdependencies between flow data and storage of water in reservoirs throughout a cascade and across time. The simulation technique of genetic algorithms was then applied to test the structure for optimal operating schedules. Different populations of solutions were tested, considering the maximization of energy generation. The results demonstrated that the proposed technique is sufficient to determine an operation schedule.

Keywords: energy operation; hydrothermal systems; genetic algorithms.

1 Introduction

In 2023, the Brazilian electricity generation system had a 60.2% share of hydroelectric origin [1]. This, combined with the growing demand for electricity and the increasing share of non-dispatchable renewable sources such as wind and solar, necessitates that the system operator, responsible for generation planning, must consider its resources wisely so that electricity is generated efficiently. It is essential to have effective resource management to ensure that all energy in contracting environments, whether free (ACL) or regulated (ACR), is supplied at lower costs and with reliability. Studies carried out by Brazil's Energy Research Company (EPE) have shown that the demand growth rate was of 4.4% in the last year [1].

Ensuring that the supply of electricity complies with the actual generation capacity of the Brazilian electrical matrix requires that the planning and operation of the system be carried out using computational tools that are compatible with the physical reality of the installed infrastructure. This imposes the need for complex studies and actions so that a strategy for generation can be created over a planning period without compromising the future, providing greater security for the supply of electricity while considering its characteristics, such as interdependency throughout space, where power plants share the same river basin, and across time, where reservoir management is essential for hedging risks of the seasonality of natural waterflow. In view of this, this article presents the development of a computational tool to help researchers and operators to find optimal management of the hydroelectric energy resource, and consequently benefit the electricity market in Brazil.

This article is organized as follows: initially a brief introduction to the operation planning problem. The mathematical formulation necessary is presented in Section 1. Section 2 presents the proposed computational model for energy planning applications. Previous years' work, considering the database structure, is introduced in Section 3. In Section 4, a brief presentation of the genetic algorithms utilized. In Section 5, a case study is shown for a set of power plants at the same basin belonging to Brazil. Finally, the article concludes by presenting the next steps to be consolidated as well as the benefits to be obtained by the use of this structure.

2 Proposed Approach

The method used in this article to describe the water-based energy resources in the computational model involves the representation of power plants using real data. This is achieved by obtaining data through a proprietary platform named 'Energ.IA'. This is a computational tool based on intelligent techniques under continuous development at UFABC, at the Laboratory of Bioinspired Technology and Solutions – LabBITS (www.ia.abc.br).

The implementation of this platform was developed by accessing model parameters remotely via a REST ("Representational State Transfer") API ("Application Programming Interface"), which are continuously updated into the Energ.IA database from the official planning software [4, 5] provided monthly by CCEE - Electrical Energy Commercialization Chamber.

Given the Brazilian energy system's growth and changes, the data representing the system varies over time. For simplicity, the case study here presented uses static scenarios.

The data is organized in Java objects, whose parameters are necessary for calculating hydroelectric energy conversion (average MWh at a given month), that can be accessed for the development of any new applications. The mathematical formulation with the parameters of the hydraulic plants necessary for energy calculation is presented in the following section.

2.1 Mathematical Formulations

Based on the data provided by CCEE [3], the goal of this paper is to develop an application for optimization of energy generation at a given hydroelectric power plant, which can be achieved through the following equations:

For obtaining the energy generated by a power plant, the following steps are necessary:
Given that reservoir measurement is often made by volume, the altitude quota is defined by the difference in level between the water surface of the reservoir and the surface of the ocean, and, depending on the storage, the corresponding quota is obtained through the quota-volume polynomial, as shown in Equation 1:

$$COTA_{J,t}^{Vol_{J,t}} = PCV_{J,1} + PCV_{J,2}.Vol_{J,t} + PCV_{J,3}.Vol_{J,t}^{\;2} + PCV_{J,4}.Vol_{J,t}^{\;3} + PCV_{J,5}.Vol_{J,t}^{\;4} \qquad (1)$$

where:

$PCV_{J,n}$: nth coefficient of the quota-volume polynomial of the power plant J (m x hm³).

$COTA_{J,t}^{Vol_{J,t}}$: Quota of the power plant J associated with the volume $Vol_{J,t}$ by the quota-volume polynomial in the respective instant t (m).

$Vol_{J,t}$: Volume of the reservoir J in the instant t (hm³).

The average quota between two volumes is calculated according to the equation:

$$COTAMED_{J,t}^{Vol_{J,t}} = \int_{Vol_{J,t-1}}^{Vol_{J,t}} COTA_{J,t}^{Vol_{J,t}} d_{VOL} \Big/ \left(Vol_{J,t} - Vol_{J,t-1}\right) \qquad (2)$$

where:

$COTAMED_{J,t}^{Vol_{J,t}}$: Average quota of the power plant J associated with the average between the minimum volume and the volume ($Vol_{J,t}$) in the instant t, according to the polynomial quota-volume (m).
$Vol_{J,t}$: Minimum volume of the J power plant reservoir (hm³), in the instant t (month).

To calculate the water head relative to the quota of a power plant, the quota above sea level of the surface of the downstream river and the losses are discounted. In this case, the losses are given in meters (m):

$$HEQ_{J,t}^{Vol_{J,t}} = COTAMED_{J,t}^{Vol_{J,t}} - CFUGA_{J,t} - CPHID_J \qquad (3)$$

where:
$CFUGA_{J,t}$: Quota of the tailrace after the powerplant J at stage t (m). The tailrace can also be calculated by a polynomial that depends on the outflow. In this case the producibility becomes even more non-linear.
$CPHID_J$: Coefficient of hydraulic losses of the plant J (m).
$HEQ_{J,t}^{Vol_{J,t}}$: Equivalent water head, associated with the average quota, from the minimum volume to a given volume $Vol_{J,t}$ of plant J in stage t (m).

From the equivalent water head, it is possible to calculate the producibility, this being a unique coefficient for each power plant, which approaches the plant's performance, encompassing the hydraulic circuit, turbine, generator, transformer and auxiliary services. Thus, the greater the producibility of a plant, the greater the energy generated in relation to the energy that comes into contact with the turbine. So, the energy generated at a given height is called by Souza et al [2] as the equivalent producibility:

$$\rho_{J,t}^{eq,Vol_{J,t}} = \eta_J . HEQ_{J,t}^{Vol_{J,t}} \qquad (4)$$

where:
$\rho_{J,t}^{eq,Vol_{J,t}}$: Equivalent producibility, considering the equivalent drop height (4), obtained from the minimum volume to the given volume $Vol_{J,t}$ of plant J considered at stage t (MW/(m³/s);
η_J: Specific productibility of power plant J (MW/(m³/s) /month).

The value of the specific producibility is also provided through the database.

While dealing with flow and reservoir volume data, it is also necessary to convert m³/s to hm³/month and vice versa, where the factor ($FATOR_r$) is calculated according to the number of days in the month. In this work, an average number of days per month was adopted considering 365 days per year, resulting in a factor of about 2.63, as can be seen in the demonstration below:

$$\Delta T = \frac{365\ days.24h.60min.60s}{12months} = 2{,}628{,}000 \text{ and } FATOR_r = \frac{1\ month\ (s)}{1\ hm^3(m^3)} = \frac{2.628.000\ s}{100^3\ m^3} = 2.628 \qquad (5)$$

From the parameters provided so far, adapted from Souza et al [2], it is possible to calculate the energy generated by a hydroelectric power plant at a given stage:

$$E_{i,t} = .\, Q_{J,t} \,.\, \rho_{j,t}^{eq,Vol_{J,t}} \qquad (6)$$

where:
$E_{i,t}$: Energy generated at the system *i* at stage *t* (*MWmonth*).
$Q_{i,t}$: Flow at a given powerplant J at stage t (m³/s).

The last parameter necessary is then the downstream flow at a given power plant, being:

$$Q_{i,t} = Q_{gen,i,t} + Q_{vert,i,t} = \frac{1}{FATOR_r}\left(Vi_{i,t} - Vf_{i,t} - V_{evap,i,t}\right) + \sum_{J=1}^{\beta_i}(Q_{J,t}) + Q_{inc,i,t} \qquad (7)$$

where:
$Q_{i,t}$: Total downstream flow at a given power plant *i* at stage *t* (*m³/s*).
$Q_{gen,i,t}$: Turbined downstream flow at a given power plant *i* at stage *t* (*m³/s*).

$Q_{vert,i,t}$: Spillage downstream flow at a given power plant *i* at stage *t* (*m³/s*).
$Vi_{i,t}$: Initial volume at a given power plant *i* at stage *t* (*hm³month*).
$Vf_{i,t}$: Final volume at a given power plant *i* at stage *t* (*hm³month*).
$V_{evap,i,t}$: Evaporated volume at a given power plant *i* at stage *t* (*hm³month*).
β_i: Group of upstream power plants of a given power plant *i* at stage *t*.
$Q_{inc,i,t}$: Incremental flow at a given power plant *i* at stage *t* (*hm³month*).

The incremental flow at a given power plant is:

$$Q_{inc,i,t} = Qnat_{i,t} - \sum_{J=1}^{\beta_i} Qnat_{J,t} \tag{8}$$

where:

$Q_{nat,i,t}$: Natural flow at a given power plant *i* at stage *t* (*hm³month*).

It is also important to consider the limits for the generated flow at a given powerplant:

$$Q_{min} \geq Q_{gen} \geq Q_{max} \tag{9}$$

where:
Q_{min}: Minimum flow
Q_{max}: Number of power plants in the system *i*.

Being:

$$Q_{max} = Pinst_{j,t}^{Vol} . \left(1 - \frac{TEIFH_j}{100}\right) . \left(1 - \frac{IPH_j}{100}\right) \tag{10}$$

where:
$Pinst_{j,t}^{Vol}$: Installed power at the power plant *i* at stage *t and volume Vol* (*MW*).
$TEIFH_j$: Number of power plants in the system *i*.
$IPH_j j$

The minimum turbined flow is provided by the database and must be respected at all times, and if, at a given month, the downstream flow of a given power plant is larger than the maximum turbined flow, the flow capable of being used for energy generation is then limited by this value, and all excess will be spilled (Q_{vert}), capable of being used on a downstream powerplant.

2.2 'ENERG.IA' Database

It is the goal of the ENERG.IA platform to develop a single database, capable of providing for researchers official updated data from the electrical system, obtained directly from the CCEE repository in a file package called 'Price Decks', in which the files necessary for processing the NEWAVE program [4, 5] are collected, which is a reference for the sector. This file package is encapsulated in .ZIP format and contains text files with different data structures as well as binary data files.

To attain this, all information provided in a 'Deck' are automatically sorted and saved in the database using JAVA programming. The foundation of the architecture is an application that feeds the microservice database which, in turn, has a REST (Representational State Transfer) interface that allows a secure externalization of the standardized information contained in the database, in JSON data format.

To close the cycle, a Web Client application that acts as a consumer of the data provided by the main API after authentication was built, thus being able to use the information stored in the database to feed models and simulations in different devices. The raw files imported from the CCEE repository are either text files or binary files, which require different and more complex manipulation to extract the information.

Thus, based on the equations shown on Section 2.1, methods were developed in Java programming language, in which the parameter's values were automatically retrieved from the database. Most variables presented above are part of the power plant characteristics provided by the files 'Deck'. The parameters also include thermo electric powerplant characteristics and upstream flow data, for example. A comprehensive description of the parameters can be found in [4,5].

2.3 Objects Structure

Based on the data provided by the database and the demands on how to calculate the energy generated at a given month, for simulations with a large amount of power plants and larger timescales, an object structure was developed to facilitate method calling and tracking and comparing results, as following:

First, from 2020 up to 2022, an object structure was developed to encompass all data from a 'Deck' (i.e. hydroelectric, thermoelectric and flow data) into objects that have their data retrieved directly from the database. In 2023, methods were developed[5], based on [2], to calculate volume dependent parameters, with the goal to evaluate the total energy in an equivalent energy reservoir of power plants on the same basin. The latter was then substituted in 2024 for the following:

A powerplant object contains all variables and methods of interest for energy calculation - all the retrieved from the database and the ones described on Section 2.1.

A system object contains all hydroelectric powerplant objects to a desired study, organizing it automatically in cascades, where upstream and downstream powerplants are in order. Based on an input of desired volume at the end of a given month and flow data for each powerplant, the energy calculated at a given system organizes upstream and downstream flows on the cascade, allowing for individualized energy calculation, where flow/volume balance is obtained considering the limits on Equation 9. Based on the total energy generated by the system at the given month, if an energy demand for the system is provided, the energy deficit is supplied by a stack of thermoelectric power plants, in increasing order of cost until all demand is satisfied, providing the object with an energy cost.

Finally, a method was developed for calculating energy at a given system for the desired time period, in the scale of months. This method needs, besides from a system object, a matrix of flow data and a matrix of desired volumes, for each powerplant at each month. From this method, the total energy cost for a certain period is obtained, and it is possible to analyze individually how each powerplant behaved at each month, considering the complexities of flow usage throughout cascades.

A conceptual visualization of this structure can be seen in Image 1, below:

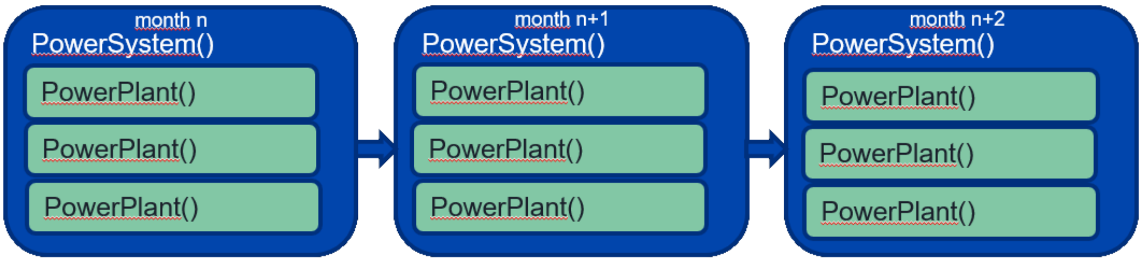


Figure 1: Visual structure of the computational model

2.4 Genetic Algorithms

The main goal of this article is to develop a structure capable of dealing with a large amount of data, maintaining individualized power plants, where data can be analyzed in an organized manner. That being said, genetic algorithms were not the focus for this case study, where heuristics based on Leite[6] were used for generating a matrix of desired volumes as input for the system, and the maximization of hydraulic energy generation was considered as the selection criteria for populating new generations.

The use of genetic algorithms is observed in four steps of this study, being:

a) All populations of desired volume percentages were initially generated randomly;
b) Half the results, the ones with most energy generated, and lowest cost, by hydroelectric powerplants, are selected for the next generation;
c) The other half is generated based on a crossover on the middle third of the desired volumes array for every powerplant, selecting randomly between two individuals of the previous generation with lowest cost;
d) For this second half, a mutation operator is then introduced, with a probability of 1%, to change any of the desired volumes to a new random volume percentage.

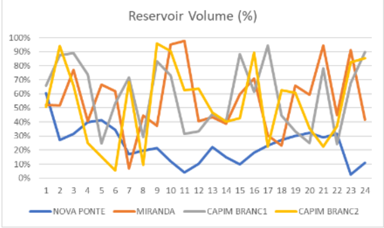
2.5 Case Study

From the presented above, a example was developed to test the capacity of the structure to provide a platform for researchers to study the characteristics of a hydroelectric system in search of satisfactory results for operation.

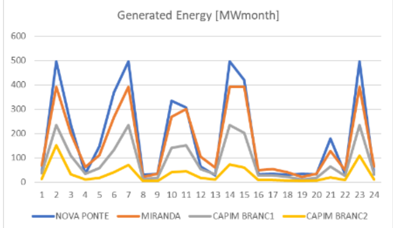
In this study, a section of the Paranaiba basin, shown in [2], was tested, where it is desired to present the general variables for analysis of the optimization problem.

For the optimization method, a group of 50 individuals was iterated for 10 generations, following the rules cited above.

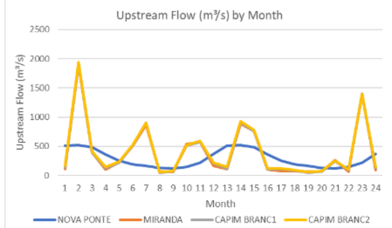
In the first step, for better visualization, considering the 4 most upstream power plants in the basin, for a period of 24 months, where flow data is considered by the long-term average for each power plant, available at [4] and at the database. It is then possible to analyze, In the Graphs 1 to 3 considering a random individual generated for random volumes:



Graph 1: Reservoir Volume Percentage at the end of the month for each power plant in the system

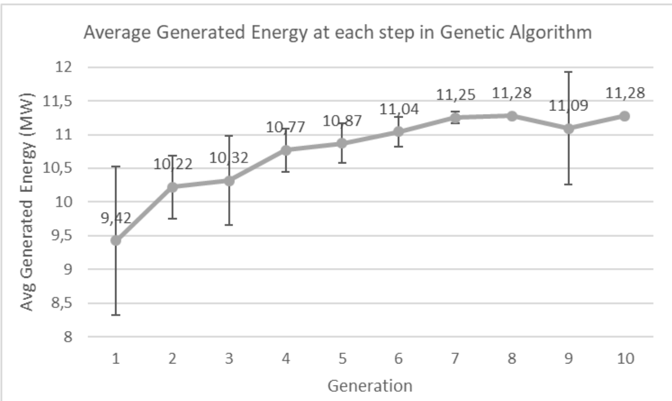


Graph 2: Generated Energy (MW) for each power plant in the system



Graph 3: Upstream flow (m³/s) data for each power plant in the system

In the graphs above, it is possible to visualize, at an individual level, how each powerplant behaves at a given month, so, in this case, it’s possible see how correlated the energy generated is between all powerplants, and how the energy generated is correlated to flow data. At the same time, in Graph 4 it is possible to analyze how the optimization method, using Genetic Algorithm, develops throughout its iterations and, adding all the energy generated throughout the planning period, the average energy generated by all individuals in each step is found, until a certain criterion is met to break the iteration.



Graph 4: Average generated energy (MW) for 10 generations of Genetic Algorithm optimization

3 Conclusions

The results presented, in the test cases, demonstrate the usability of the computational tool and the autonomy to carry out studies which are key to propose new methodologies for determining the optimal operation of the generation system. At the end of this study, all researchers at LabBITS have now available to them a more detailed and structured model to work on new studies, being able to research new optimization methodologies and an in-depth analysis of the behavior of the system.

For the next steps, more variables and restrictions need to be design so that this project can effectively be used for energy planning optimization and operation. Some variables include the capability of adding planned new power plants for operation in its analysis throughout time. Another development to be done is the inclusion of timed restrictions, such as when a power plant will be inoperative, instead of an average time period, as shown in Equation 10. Also, while this project is focused on energy generation, based mostly on flow and reservoir management, another group at LabBITS is developing a model for the energy transmission infrastructure in Brazil, so it is desired in following years that these two branches will be connected, allowing for better representation of the system.

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