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Optimal operation of the Jirau hydroelectric power plant reservoir using nonlinear optimization

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***Abstract*—Hydroelectric production is normally scheduled with respect to the demand in the power network at any time. At the hydroelectric power plant, regulating the volume of the reservoir is an important strategy to optimize the energy production. In this context, this paper proposes a control strategy for the optimal operation of the reservoir of Jirau hydroelectric power plant. This strategy is obtained using nonlinear optimization in order to maximize the production of electricity according to daily reservoir variation. To validate the model it was used historical data of the plant's flow. Results show that the model concentrated resources in the region with the highest energy demand, increasing reservoir use. On the other hand, it has preserved resources in regions of lower demand, increasing reservoir volume.**

Keywords—Nonlinear optimization, Reservoir volume policies, Hydroelectric power plant.

I. INTRODUCTION

The optimal hydroelectric power plant reservoir is a complex nonconvex optimization problem. A convex optimization problem is defined as a problem that maintains the properties of a linear programming problem. In a nonconvex problem some of the objective functions or constraints are nonlinear [1]. Nowadays, optimal use of water resources is crucial due a decrease of water and energy as a function of climate changes, especially in regions with law precipitation. In this case, headwater management practices and climate conditions can impact availability of water in the surface reservoir systems [2].

Efficient management of reservoirs is one of the most important variables of equation to energy generation from surface reservoirs. The definition of policies to operate surface reservoirs under uncertain climate conditions is the main difficulty of managing surface reservoir. The high demand for water and energy increases the complexity of managing water resources and their operation. Effective reservoir operation policies include optimize releases from reservoir or storage volume to achieve the objectives such as maximizing power generation, minimizing water deficit, flood risk, and operation costs [3].

Hydropower has become one the most important sources of clean and sustainable energy. It is one of the sources of hydroelectric energy that can meet the great demand by electricity consumption. Thus, more robust and reliable operation techniques should be developed to operate hydropower plants in order to reduce the vulnerability of the system. Robust optimization techniques have been historically introduced to maximize hydropower generation [4].

To overcome the shortcomings of linear optimization methods for solving water resources management problems the researchers have used some resources. Goal programming, chance constraint linear programming, dynamic programming and recently, the soft computing techniques [5], nonlinear programming, quadratic programming, Newton-based solutions, mixed integer programming and interior point methods to solve problems [6, 7].

In this context, the purpose of this work is to explore the use of nonlinear optimization based on quadratic programming. To obtain an optimal strategy for controlling the reservoir of the Jirau Hydroelectric Power Plant (Jirau HPP) installed on the Madeira River in the State of Rondônia in the Northern Region of Brazil. The results obtained in this work will be incorporated into a Cyber Physical System (CPS) [8] that makes up a Digital Twin (DT) [9, 10] from the Jirau HPP plant. This DT is part of the Jirau 064/2018 project, ANEEL PD-06631-0007/018.

This paper is organized as follows. Section II presents the reservoir, turbine and spillway models. Section III presents the demand profile used and the optimization model. Finally, in Section IV and V the results conclusions are presented.

II. RESERVOIR AND OPTIMIZATION MODELS

The reservoir model can be represented by the scheme shown in Figure 1. As can be seen, water enters the reservoir through the natural flow of the river. The reservoir's function is to store incoming water, that is, it is the part of the system that stores potential gravitational energy [11]. The water can come out of the reservoir being poured and or turbined. The outlet through the spillway occurs through the direct flow of water to the natural course of the river, being controlled by gates capable of retaining or releasing the water and controlling the level of the reservoir[12, 13, 14, 15]. The

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outlet through the turbine is used to generate electricity, using the gravitational potential energy stored in the reservoir to move the turbine and convert that energy into electricity. Electricity is supplied to the system according to the current demand. In this way, it is possible to control the flow of water through the spillway and the turbine in order to maximize power in the long run [16].

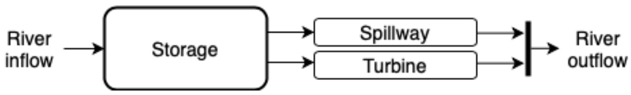

Fig. 1. Schematic representation of the reservoir

Quadratic programming is a nonlinear programming with quadratic objective function and linear constraints. This algorithm provides a solution even from an infeasible initial starting point [17]. The model to be used for the representation of the system dynamics can be seen in Equations (1) and (2):

$$E(t)=T(t-1)\ [\ k_1\ (\ S(t) - S(t-1)) + k_2 \tag{1}$$

$$S(t) = S(t-1) + \Delta t\ [\ F(t-1)\ - V(t-1) - F(t-1)], \tag{2}$$

Equation (1) describes the power generated (*E*) in time (t) with the turbine flow (*T*) and the reservoir level (*S*). The constants k_1 and k_2 are empirically chosen to weigh the relationship between the turbine flow and the reservoir. Equation (2) describes the volume of the reservoir (*S*) at the time (t) with the portion of the reservoir volume in *t-1* aggregated to the inflow (*F*), the flow rate (*V*) and the turbine flow rate (*T*) in a discretized time step Δt. Therefore, the amount of energy produced depends on the level of the reservoir, the amount of water flowing through the turbine and the spillway. This means that the greater the amount of water in the reservoir, the more energy can be produced. However, this amount is determined by the current energy demand. Such demand is supplied by the National Interconnected System (NIS) [18, 19], which is formed by a group of other plants spread over the Brazilian territory. The SIN then supplies energy to users according to their needs, undergoing variations throughout the day. In this scenario, the proposal presented here aims to obtain an optimal energy generation strategy, using the model previously described according to the variation of the NIS's power demand.

III. CASE STUDY

The Madeira River is located in the north of Brazil. This river has enormous hydroelectric potential, with flow rates reaching 60,000 m³/s. Due to the local geography, being predominantly plain, the dams built on this river have a low nominal fall, approximately 15 meters. A creative solution to take advantage of the river's hydroelectric potential was to place a large number of turbines with lower power. In the case of the Jirau Plant, there are 50 generating units [20]. One way to make better use of the potential already installed is to optimize the use of water that arrives at the plant. In this way, this article proposed the use of a non-linear optimization technique in order to maximize the production of electric energy. For simplicity of modeling, the 50 generating units and the 18 spillway gates will be represented as a single generating unit and a single gate.

To validate this strategy, a case study was made using real data from the Jirau Hydroelectric Power Plant, obtained from the plant's flow history from 10/13/19 to 10/26/19. The NIS's power demand was also obtained on the website of the National System Operator (NSO) [21] for the same 13 days, as shown in Figure 2.

Figure 2 shows how the energy demand constantly changes throughout the day, causing an overload on the system at times. Thus, it is possible to prioritize the generation of energy in times of overload [22, 23], that is, to reserve water in periods of less demand and to turbine a greater amount of water in periods of greater demand, resulting in a greater generation of energy.

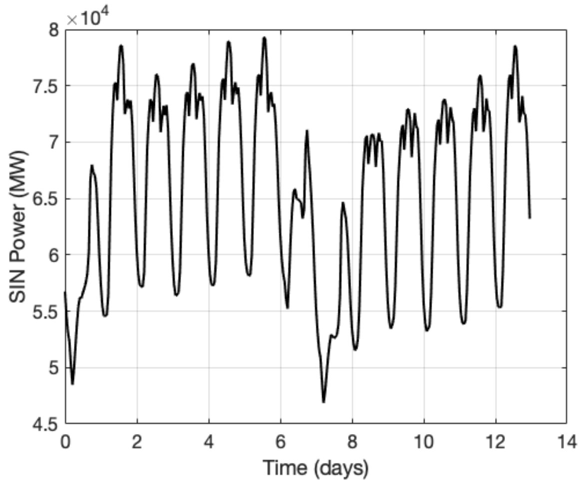

Fig. 2. National Interconnected System (NIS) Power Demand from 10/13/19 to 10/26/2019.

In this context, it is possible to define the optimization problem considering the NIS demand as a function to be optimized according to the plant's dynamics (Equations (1-2) and the restrictions presented in Equations (3-7):

$$0 < T < 27500\ m^3/s\,, \tag{3}$$

$$0 < V, \tag{4}$$

$$3000\ m^3/s \leq T + V\,, \tag{5}$$

$$124{,}983 * 10^6\ m^3 < S < 161{,}066 * 10^6\ m^3\,, \tag{6}$$

$$S(0) = S(t)\,, \tag{7}$$

It is worth mentioning that the studied scenario considered the variation of the reservoir between the 82.5 m and 85 m quotas.

All restrictions are linear, so it is possible to express them in matrix notation. However, the objective has non-linear characteristics, which indicates the need for a quadratic

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solver. This evidence is again verified with the Hessian matrix being constant, that is, the values of the matrix are independent of the variables. The solver used for this nonlinear optimization was quadratic programming, through the quadprog function of the MATLAB software.

IV. Optimization Results

Figure 3 shows the optimal flow results generated by the proposed model. One can see that the model allocates the affluent flow in electricity generation. Moreover, the turbine flow changes in time according to the NIS's load variation. All the water from the reservoir was used to generate electricity (the spillway remained closed).

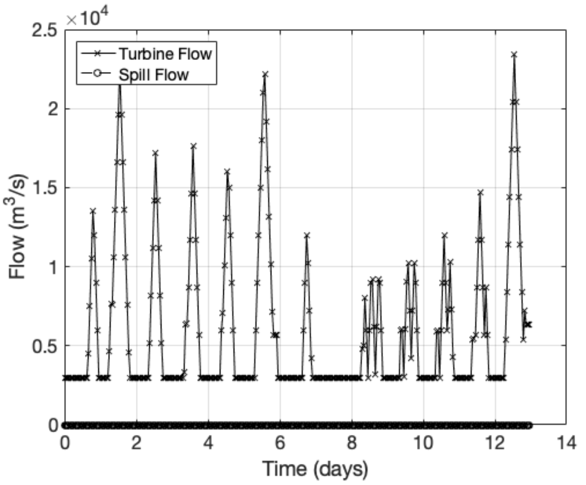

Fig. 3. Results of optimal affluent flow.

The volume of the reservoir used by the proposed strategy is depicted in Figure 4. It is possible to verify the variation of the total volume from the reservoir over a time frame, which follows the variation of the NIS power demand. Therefore, following this reservoir control policy, energy generation will be optimized for periods of high energy demand, increasing the electricity production.

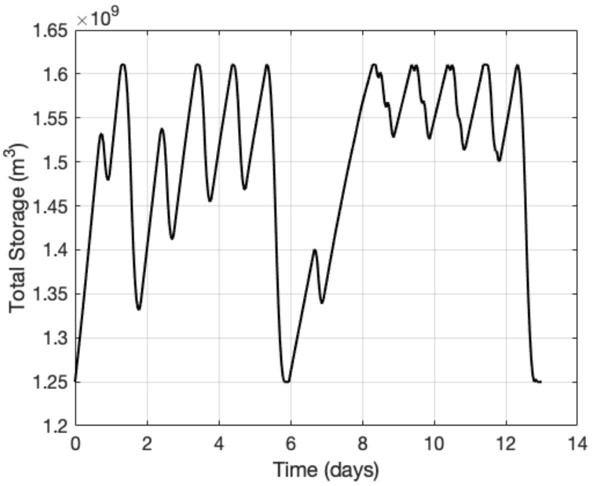

Fig. 4. Ideal storage behavior through time obtained by the proposed model.

For comparison purposes, the accumulated power was calculated for the plant's original energy generation and for the optimization proposal, as shown in Figure 5. This gain is calculated by adding the energy produced each day by both generation models. The optimized model provides a significant increase in the amount of generation at the end of the period. The same affluent flow that passed through the plant's bus allowed a result 14% higher than the original generation in the same period. Considering that there is another hydroelectric plant downstream on the same river, such optimization could be used in the cascade of plants on the Madeira River and considerably increase the energy potential of the system.

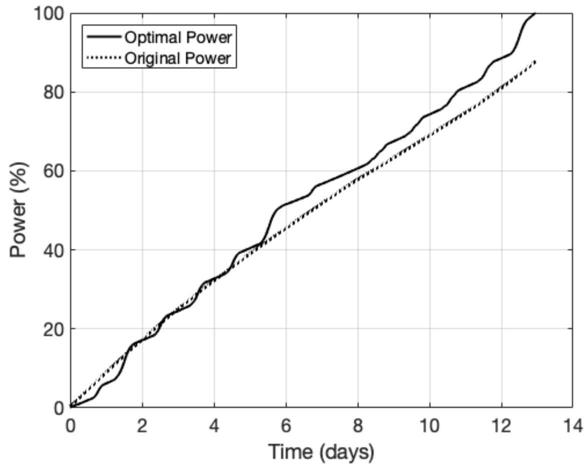

Fig. 5. Percentage of power generated.

Finally, the results obtained were compared with the actual generation of the plant in the same period. Figure 6 shows the original generation of the plant versus the optimized generation following the NIS's load profile. It is possible to observe that the electric's system demand varies in hours during the day. Comparing it to Figure 2, it is clear that the proposed strategy maximizes the generation of the plant in times of greatest demand, proving to be valid for use in a real situation.

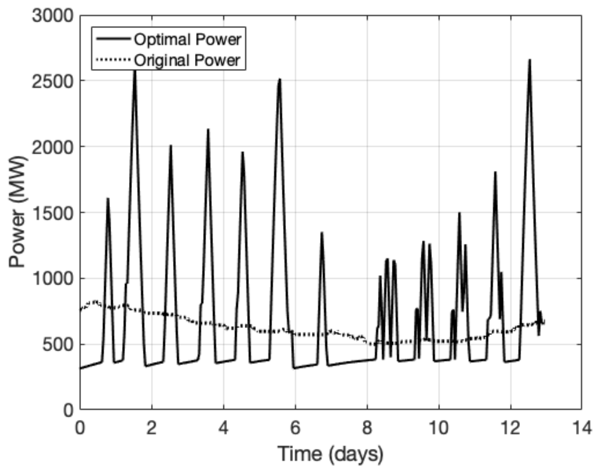

Fig. 6. Optimal power generation.

This work presents a control strategy for optimal operation of the Jirau hydroelectric plant reservoir. Such strategy was obtained using non-linear optimization to maximize the production of energy based on daily reservoir variation. The model provides efficient usage of the total volume of the reservoir and the turbine flow based on the historical data. Comparing the results from the model with

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the energy demand from NIS, the strategy corroborates with its behavior. Thus, the model shows great potential for use in the real dynamics of the plant. Therefore, it is possible to concentrate resources in the region with the highest energy demand, significantly improving energy production.

It is worth mentioning that the amount of water in the reservoir was the same for the NIS and the model proposed. Therefore, there is no need to change the plant's infrastructure to obtain the obtained efficiency. There was still a significant gain for the NIS, since it received energy on demand. For future works, a study could be performed considering the variation of the reservoir, so that it would be able to operate from 82.5 m leveling up to 90 m.

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