

An Approach Based on Takagi-Sugeno Fuzzy Inference System Applied to the Operation Planning of Hydrothermal Systems

Ricardo A. L. Rabêlo
and Ricardo A. S. Fernandes
and Adriano A. F. M. Carneiro
University of São Paulo
Engineering School of São Carlos
São Carlos, São Paulo, Brazil

Rosana T. V. Braga
University of São Paulo
Department of Computing Science
São Carlos, São Paulo, Brazil
Email: rrtvb@icmc.usp.br

Email: ricardor_usp@yahoo.com.br, ricardo.asf@gmail.com, adriano@sel.eesc.usp.br

Abstract—The operation planning in hydrothermal systems with great hydraulic participation, as it is the case of Brazilian system, seeks to determine an operation policy to specify how hydroelectric plants should be operated, in order to use the hydroelectric resources economically and reliably. This paper presents an application of Takagi-Sugeno Fuzzy Inference Systems to obtain an operation policy (PBFIS - Policy Based on Fuzzy Inference Systems) that follows the principles of the optimized operation of reservoirs for electric power generation. PBFIS is obtained through the application of an optimization algorithm for the operation of hydroelectric plants. From this optimization the relationships between the stored energy of the system and the volume of the reservoir of each plant are extracted. These relationships are represented in the consequent parameters of the fuzzy linguistic rules. Thus, PBFIS is used to estimate the operative volume of each hydroelectric plant, based on the value of the energy stored in the system. In order to verify the effectiveness of PBFIS, a computer simulation model of the operation of hydroelectric plants was used so as to compare it with the operation policy in parallel; with the operation policy based on functional approximations; and also with the result obtained through the application of the optimization of individualized plants' operation. With the proposed methodology, we try to demonstrate the viability of PBFIS' obtainment and application, and with the obtained results, we intend to illustrate the effectiveness and the gains which came from it.

Index Terms—Takagi-Sugeno, Fuzzy Inference System, Operation Planning, Hydrothermal Systems, Operation Policy.

I. INTRODUCTION

The operation planning of hydrothermal systems aims to determine an operation policy to specify how thermal and hydraulic subsystem should be operated so that the available resources for electric power generation are used efficiently. The problem of the planning is very complex due to several aspects, such as: the stochasticity of the water inflows and of the electric power market; the hydraulic interconnection of the hydroelectric plants in a cascade; the nonlinear operational characteristics of hydroelectric and thermoelectric plants; the dynamic relationship among the operation decisions taken along the whole horizon; and the transmission constraints of the electric system [1], [2], [3], [4].

In hydrothermal systems with great hydraulic participation, the operation policy seeks to replace the generation of complementary origin (thermo electrical plants, import of energy from other systems and the deficit) by hydroelectric origin generation, whenever possible [5]. Thus, in these hydrothermal systems, the operation planning has to determinate an operation policy for the reservoirs of the generation hydroelectric system as a fundamental point. The operation policy adopted in Brazilian electric power system is the Parallel Policy (PP) [6]. In this operation policy, the reservoirs are operated in parallel, which should maintain the same percent level of their useful volumes. This operation policy has its simplicity as its greatest attraction. However, it doesn't obey the principles of the optimized operation of the reservoirs for electric power generation [7], [8], [9].

To obtain an operation policy that represents the optimized behavior of the reservoirs, initially, the operation of the hydroelectric system is optimized under distinct operative conditions. With this optimization we can get a group of operation points that relate the energy stored in the hydroelectric system with the state of the reservoir of each hydroelectric plant. Figures 1 and 2 exhibit representative points of the optimized operation of some Brazilian power plants.

So that the group of operation points can be used as indicative for an operation policy, the adjustment of functions that represent the behavior of the optimized operation of the reservoirs will be necessary. Several works are related to the obtainment of operation policies, only differentiating in the employed technique for the adjustment of the points obtained relative to the optimized operation. In [10], the authors use third degree polynomial functions to adjust the points obtained with the optimization of the operation in order to obtain the operation policy. In [11], the authors make the adjustment of the points, obtaining polynomial and exponential functions to represent the operational policy whereas in [2], [12], [13], the authors use the method of the least squares in the adjustment of the polynomial, exponential and linear functions. In [14], [15],

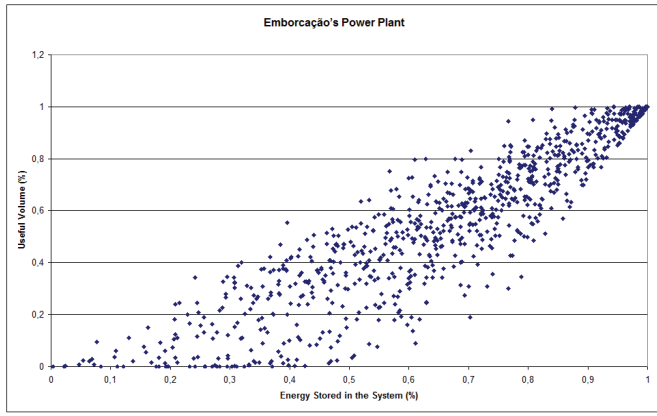


Fig. 1. Representative points of the optimized operation of Emborcação's power plant.

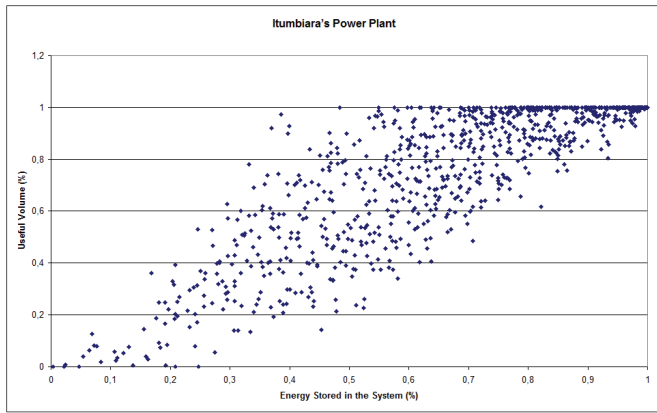


Fig. 2. Representative points of the optimized operation of Itumbiara's power plant.

Artificial Neural Networks (ANNs) are used, more specifically the SONARX model, for the obtainment of an operation policy that follows the principles of the optimized operation.

This paper presents an application of Takagi-Sugeno (TS) Fuzzy Inference Systems [16], responsible for obtaining an operation policy (PBFIS - Policy Based on Fuzzy Inference System) that represents the optimized operation of reservoirs for electric power generation [17]. The parametric functions in the consequents of the TS fuzzy rules and the adjustment easiness starting from a set of input and output data makes the TS fuzzy inference systems be related to the functions approximation task [18]. So as to illustrate the effectiveness of PBFIS, it was evaluated comparatively with the Parallel Policy (PP); with the operation policy based on functional approximations that use polynomial and exponential functions (policy based on polynomial and exponential functions - PBPEF), obtained through the method of the least squares; and also with the results obtained through the optimization of the operation of hydroelectric plants. Hence, we try to demonstrate the viability of the obtainment and application of PBFIS, as well as the energy gain that came from it.

Section 2 presents the problem of the operation planning of hydrothermal systems focusing on the adopted planning horizon, the mathematical formulation, and the operation policy for hydroelectric systems, besides presenting the hydroelectric system used in the case studies of this paper. In the Section 3, some foundations of the Takagi-Sugeno fuzzy inference system are presented, as well as the proposed fuzzy system. Section 4 brings the application of the operation policy for the chosen hydroelectric system, emphasizing the main results of the case studies. Section 5 presents the discussions of the work, followed by Section 6, in which the conclusions and final observations of the work are presented as a whole.

II. OPERATION PLANNING OF HIDROTHERMAL SYSTEMS

A. Hydroelectric System

Figure 3 illustrates the hydroelectric system used in the case studies of this paper. This system is composed of some hydroelectric plants of the Brazilian system. It is pinpointed that the chosen hydroelectric system can be characterized as a complex system, because it contains interlinked plants in parallel and in cascade.

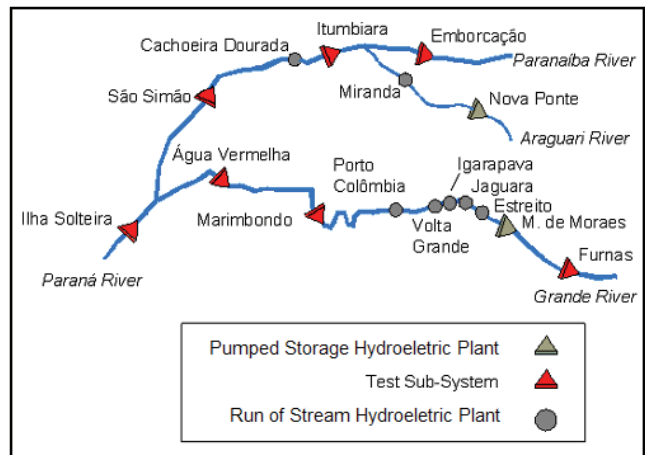


Fig. 3. Hydroelectric system used.

B. Planning Horizon

In this paper, the operation planning was adopted with five-year horizons (monthly discretized), but considering the individualized representation of the hydroelectric plants. The simplification of the composite representation of the system makes the hydroelectric generating system not be used in the most possible efficient way, once the equivalent reservoir of energy doesn't get to represent the individual operative characteristics of the plants. Thus, the individualized representation of each hydroelectric plant is important.

C. Mathematical Formulation

The operation planning of hydrothermal systems, with individualized representation of the hydroelectric plants and with

deterministic water inflows can be formulated according to the following optimization problem:

$$\min \quad \sum_{t=1}^T CVP_t \cdot 0,5 \cdot \Phi(D_t - H_t)^2 + V(x_T) \quad (1)$$

$$s.a. \quad E_t = D_t - H_t, \quad (2)$$

$$H_t = \sum_{i=1}^N k_i \cdot hl(x_{i,t}^{med}, u_{i,t}) \cdot \min[u_{i,t}, q_{i,t}^{max}], \quad (3)$$

$$x_{i,t} = x_{i,t-1} + (y_{i,t}^{inc} + \sum_{k \in \Omega_i} u_{k,t} - u_{i,t} - x_{i,t}^{evap}) \cdot [\frac{\Delta t_t}{10^6}], \quad (4)$$

$$u_{i,t} = q_{i,t} + v_{i,t}, \quad (5)$$

$$x_{i,t}^{min} \leq x_{i,t} \leq x_{i,t}^{max}, \quad (6)$$

$$u_{i,t}^{min} \leq u_{i,t} \leq u_{i,t}^{max}, \quad (7)$$

$$q_{i,t}^{min} \leq q_{i,t} \leq q_{i,t}^{max}, \quad (8)$$

$$x_{i,0} \text{ given}, \quad (9)$$

onde:

- T : number of intervals of the planning horizon;
- N : number of hydroelectric plants;
- CVP : coefficient of present value;
- E_t : total thermal generation [MW];
- H_t : total hydroelectric generation [MW];
- D_t : demand (electric energy market) [MW];
- $x_{i,t}$: volume stored in the reservoir i at the end of the interval t [hm³]. The values of the initial volumes of the reservoirs are given;
- $x_{i,t}^{med}$: medium volume stored in the reservoir i in the interval t [hm³];
- $x_{i,t}^{evap}$: volume evaporated in the reservoir i in the interval t [hm³];
- $hl_{i,t}$: net water head of the plant i in the interval t [m];
- $y_{i,t}^{inc}$: incremental water inflow to the reservoir of the plant i in the interval t [m³/s];
- $q_{i,t}$: turbinated flow of the plant i in the interval t [m³/s];
- $u_{i,t}$: flow release of the plant i in the interval t [m³/s];
- $v_{i,t}$: spill flow of the plant i during the interval t [m³/s];
- $x_{i,t}^{max}, x_{i,t}^{min}$: maximum and minimum limits of stored volume for the reservoir of the plant i at the end of interval t [hm³];
- $u_{i,t}^{max}, u_{i,t}^{min}$: maximum and minimum limits of the flow release for the plant i in the interval t [m³/s];
- $q_{i,t}^{max}, q_{i,t}^{min}$: maximum and minimum limits of turbinated flow for the plant i in the interval t [m³/s];
- Δt_t : number of seconds in the interval t [s];
- Ω_i : group of indexes of the plants immediately upstream of plant i .

The objective function is composed of two terms, which represent the operational cost during the horizon planning (Φ) and the future costs associated with the final storage condition from hydroelectric plants to reservoirs (V). As the Brazilian system is a hydrothermal system greatly predominant of hydraulic origin generation, for our purposes, complementary generation system is being used by an equivalent thermoelectric plant that substitutes all non-hydraulic system [19]. Thus, the operational cost is represented by a single cost

function of non-hydraulic sources. Future cost is a terminal condition used in the optimization models of the operation to balance the use of water during the planning horizon and its future use [20].

The equality (2) represents the constraints towards the electric power demand in the interval t . The total hydraulic generation of the hydroelectric system is represented by equation (3), given by the sum of the hydraulic production functions of each hydraulic plant. The equation (4) represents the water balance in the reservoir. The output flow of the plant corresponds to the flow released and is equivalent to the sum of the turbinated flow with the spilled flow and it is represented in equation (5). The constraints (6) and (7) represent the storage and the released flow limits of the hydroelectric plants. The limits presented in these inequations vary in time, because these reflect the operational restrictions of the plant and other restrictions associated with the multiple use of water, such as: irrigation, control of floods, navigation, etc. Restriction (8) represents the minimum and maximum limits of turbinated flow, which can be associated with physical restrictions of the plant itself or electric restrictions.

D. Hydroelectric Systems Operation Policy

The operation policies for hydroelectric systems are present in several stages of the operation planning of hydrothermal systems. They are necessary in the aggregation procedure for obtainment of the equivalent reservoir [21], [22], in the simulation of the operation to disaggregate the goals of hydraulic generation of the equivalent reservoir among all the plants [10], and for the evaluation of the performance of the hydroelectric system in several conditions [23], [24]. Additionally, operation policies are also used in the expansion planning of the Brazilian hydrothermal system.

The operation policies for hydroelectric systems try to determine the amount of electric power produced by each one of the plants, through the definition of the storage state of each reservoir. The operation policy can be understood as a group of operation rules, one to each plant (or reservoir) of the system, which defines how these plants will be operated in a coupled way. To implement the coupling in the operation of hydroelectric systems, a global parameter is defined, denominated coupling factor of the operation among the plants, denoted by λ_t . The coupling factor represents the percentage of storage of the system in a certain interval t , and it is calculated (Equation 10) as the proportion between the energy stored in the system (ESS_t) and the maximum energy stored in the system (ESS^{max}), resulting in the values in the interval: $0 \leq \lambda_t \leq 1$.

$$\lambda_t = \frac{ESS_t}{ESS^{max}} \quad (10)$$

With the value of λ , the volume of each reservoir can be determined by the following equation:

$$x_{i,t}(\lambda_t) = x_{i,t}^{min} + f_i(\lambda_t) \cdot (x_{i,t}^{max} - x_{i,t}^{min}) \quad (11)$$

Where:

- $x_{i,t}(\lambda_t)$: operative volume of plant i in the interval t ;
- $f_i(\lambda_t)$: operation rule of the reservoir of plant i as function of the parameter λ_t . It expresses the rules of emptying/filling of the reservoir together with the other reservoirs of the hydroelectric system.

III. TAKAGI-SUGENO FUZZY INFERENCE SYSTEMS

The fuzzy inference systems are based on production rules that make use of the linguistic variables [25] to execute a process of decision making. The operation of fuzzy inference systems can be divided in three stages: fuzzification, inference procedures and defuzzification.

In the fuzzy inference systems, usually, crisp (or precise) inputs are considered resulting from observations or measurements. Because of that, it is necessary to make a conversion (fuzzification) of those data for the fuzzy input sets. This way, the fuzzification is a mapping of the domain of the crisp input variable for the fuzzy domain, to attribute linguistic values (vague or qualitative descriptions) defined by membership functions to the entrance variables. The inference procedure is responsible for processing the fuzzy input data together with the production rules, so as to infer the contributions in the fuzzy output of the inference system. A typical production rule of Takagi-Sugeno fuzzy inference model is: if x is F and y is G , then, $z = f(x, y)$, where F and G are fuzzy sets and f is a polynomial function of x and y . The inference procedure in the Takagi-Sugeno model, specifically, consists of obtaining all the individual contributions z_i coming from each one of the fired rules. After this stage, we should combine all of the individual contributions to get the final answer z . Thus, the numeric output is calculated directly by the sum of the outputs pondered by the degree of fired of each rule (μ_i). Therefore, the defuzzification process is unnecessary [26]. This model was proposed as an effort to develop a systematic approach so as to generate fuzzy rules starting from a group of input and output data [27].

The fuzzy inference systems implemented have as input linguistic variable the *ESS*, defined in the group of linguistic terms (Very Low, Low, Medium, High and Very High)(Figure 4).

In this paper, we specialized for each one of the 7 plants (Figure 3), a Takagi-Sugeno fuzzy inference system. Each TS system is composed of 5 disjunctive inference rules. The syntax of the rules base of the fuzzy systems implemented is represented by the following linguistic conditional declarations:

- Rule 1: If (*ESS é Very Low*), Then $z_1 = f_1(ESS) = a_1 \cdot ESS + b_1$
- Rule 2: If (*ESS é Low*), Then $z_2 = f_2(ESS) = a_2 \cdot ESS + b_2$
- Rule 3: If (*ESS é Medium*), Then $z_3 = f_3(ESS) = a_3 \cdot ESS + b_3$
- Rule 4: If (*ESS é High*), Then $z_4 = f_4(ESS) = a_4 \cdot ESS + b_4$

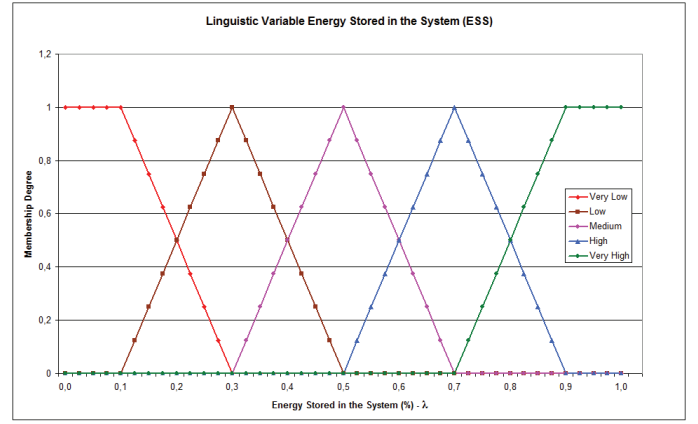


Fig. 4. Input linguistic variable representing the energy stored in the system.

TABLE I
PARAMETERS OF THE CONSEQUENTS OF THE PRODUCTION RULES OF THE FUZZY INFERENCE SYSTEM TO THE PLANT OF EMBORÇAÇÃO.

i	ESS	a	b
1	Very Low	0,5272	-0,0188
2	Low	0,8928	-0,1013
3	Medium	1,0796	-0,1776
4	High	1,2216	-0,2690
5	Very High	1,4516	-0,4533

- Rule 5: If (*ESS é Very High*), Then $z_5 = f_5(ESS) = a_5 \cdot ESS + b_5$

With the optimization of the hydroelectric system operation, we obtain a set of operation points, which relate the stored energy of the hydroelectric system to the operative volume of each reservoir. For each one of the 5 rules that compose each fuzzy system, linear regression is applied at the points belonging to its activation domain, using the known input/output points, in order to determine the parameters (a_i, b_i) of each one of the ($5 \cdot N$) polynomial functions relative to the consequent of N fuzzy systems ($N = 7$). Tables I, II and III present the parameters of the consequents of the fuzzy production rules relative to the policy proposed for some reservoirs of the hydroelectric system used.

With the determination of the 70 parameters of the consequents of the linguistic rules (a_i, b_i), the fuzzy system can be put to operation. In the particular matter, the TS fuzzy inference system i determines the operation rule of the plant i of the hydroelectric system:

$$f_i(\lambda) = \frac{\sum_{j=1}^5 (z_j \cdot \mu_j)}{\sum_{j=1}^5 \mu_j}; i = 1, \dots, N \quad (12)$$

IV. CASE STUDIES

In this paper, a computer model was used to simulate the operation of hydroelectric systems, so as to allow the performance evaluation of the proposed operation policy (PBFIS). The simulation model used is part of a computer tool that has been developed by the authors for the accomplishment

TABLE II
PARAMETERS OF THE CONSEQUENTS OF THE PRODUCTION RULES OF
FUZZY INFERENCE SYSTEM FOR TO THE PLANT OF ITUMBIARA.

i	ESS	a	b
1	Very Low	1,4329	-0,0757
2	Low	1,4357	-0,0744
3	Medium	1,0728	0,0724
4	High	0,9702	0,1341
5	Very High	0,4968	0,5114

TABLE III
PARAMETERS OF THE CONSEQUENTS OF THE PRODUCTION RULES FUZZY
INFERENCE SYSTEM TO SÃO SIMÃO'S PLANT.

i	ESS	a	b
1	Very Low	2,5578	0,1792
2	Low	0,7766	0,5879
3	Medium	0,1661	0,8414
4	High	0,1414	0,8584
5	Very High	0,1008	0,8924

of studies related to the operation planning of hydrothermal systems. The tool comprehends, besides the simulation model, a model of optimization of the hydrothermal systems operation [28]. The optimization model is used to determine the optimized operation of reservoirs and is inspired in algorithms of optimization designed for the operation planning of hydrothermal systems [29], [30]. It should be stressed that the authors applied a development process (UML Components) [31] based on software components [32] for the construction of the computer models, in order to guide the development of the tool.

The simulation of the operation intends to verify how a hydroelectric system would behave in case it were submitted to certain operation conditions (electric power market, operation policies, operative restrictions, initial volume, etc.). Thus, to make the comparison among the proposed policy (PBFIS), the policy based on polynomial and exponential functions (PBPEF), and the parallel policy (PP); the simulations of the operation are accomplished under the same operation conditions. Therefore, the differences of behavior in the operation of the hydroelectric system will only result from the policies used.

A. Operation Conditions

Five case studies were realized, with the intention of accomplishing a comparison among the three operation policies implemented in the simulation model, under several hydrological conditions. The goal of hydraulic generation (or electric power market) is said to be equal to the hydraulic generation provided by the operation optimization model, for the periods of the report from 1936 to 1941; 1951 to 1956; 1971 to 1976; 2000 to 2005 and with data of LTA (Long Term Average). The natural water inflow corresponds to the flows verified for the same periods of the report. The month of May was adopted (beginning of the dry period for the hydrographic basin of the Brazilian southeastern system) as the beginning month for all case studies. For additional comparisons, the optimization

of the hydroelectric system operation was accomplished with water inflows really occurred in the periods, in order to obtain the solution with the perfect knowledge of the water inflows for the whole planning horizon. We emphasize that the solution obtained through the optimization model corresponds to the superior performance limit in the use of the hydroelectric generation resources. We considered in all the case studies that the initial volume stored in the reservoirs were the same as the operative maximum volume.

B. Results

1) *Volume Stored in the Reservoirs:* Figures 5 and 6 exhibit the trajectories of reservoirs' useful volume of some plants of the hydroelectric system considered for test. A differentiated behavior can be observed for each plant's reservoir, in which the oscillation of the reservoirs' volume is made in function of its positioning in the cascade. In the figures, one can visualize that the more upstream reservoir (Emborcação) presents a smaller storage level during the planning horizon. The plant of Itumbiara, in the intermediate position, presented a medium storage level, while the plants of São Simão downstream, presents lower emptying level (higher storage level).

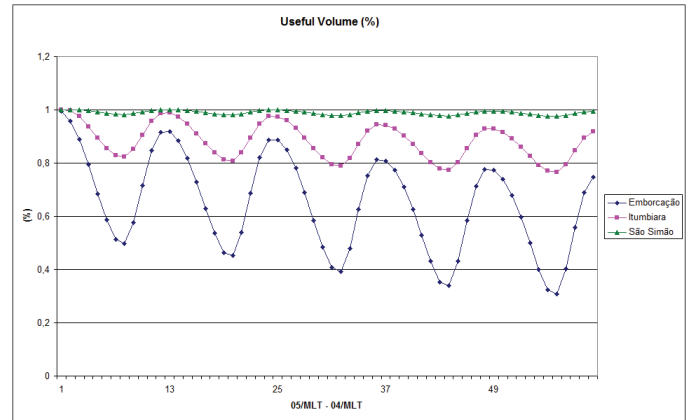


Fig. 5. Trajectories of useful volume in some reservoirs of the hydroelectric system for MLT.

With PBFIS, the downstream plants, whenever possible, remain full, so as to maintain high productivity and, thus, value the water that goes by them. As the energy stored at a plant is valued by the productivity of all downstream plants, the net water head of the plant more downstream, for instance, affects the stored energy of all plants of the cascade. Therefore, the consequent parameters of the fuzzy inference system are adjusted to prioritize higher storage levels in the upstream to the downstream reservoirs in the cascade of plants.

2) *Deficit of Energy Stored in the System:* Figure 7 illustrates the deficit path of stored energy (in %) in the system for the simulations of the operation accomplished with the three implemented policies, using the LTA. The deficit of energy stored in the system is calculated as the subtraction between the value of the stored energy resulting through the optimized solution, and the values of the stored energy resulting from the

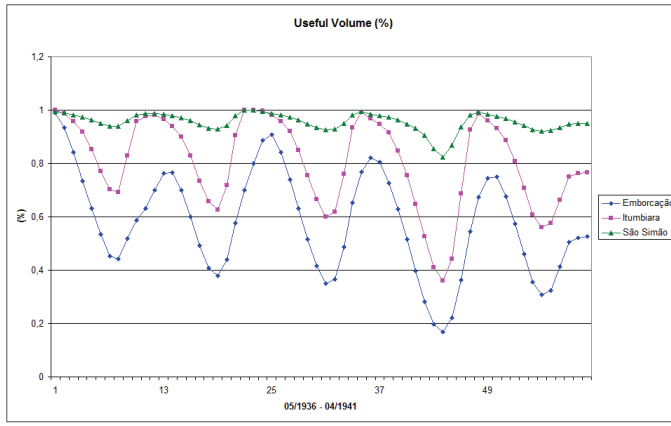


Fig. 6. Trajectories of useful volume in some reservoirs of the hydroelectric system 1936 to 1941.

application of operational policies implemented in the simulation model. A more severe emptying of the group of reservoirs can be noticed when using the parallel policy, followed by a less rigorous emptying when using PBPEF, and an even less accentuated emptying using PB, what implicates a larger efficiency in the use of generation hydroelectric resources, through the proposed policy (PBFIS).

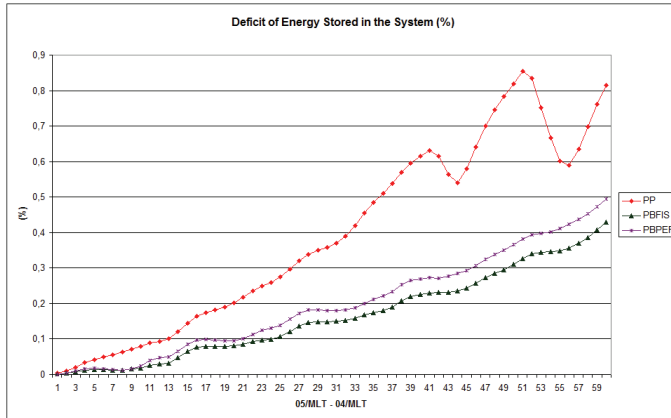


Fig. 7. Trajectories of the deficit of energy stored in the system for MLT.

Table IV allows the reader an additional comparison, in order to verify the efficiency of each operation policy with the optimized solution numerically. Considering the planning horizon involving the years 1936 - 1941, 1951 - 1956, 1971 - 1976, 2000 - 2005 and LTA (05 years of medium flows), we can confirm the greatest efficiency supplied by the proposed policy when compared with the parallel policy, in the use of generation hydroelectric resources. It is noteworthy that when compared with PBPEF, PBFIS only presents more reduced levels of stored energy (or a higher stored energy deficit) in the horizon from 1971 to 1976.

In Figure 8, we can verify the best use of generation hydroelectric benefits, for the proposed policy, where it is noticed that the emptying of the reservoirs is much more

TABLE IV
AVERAGE OF ENERGY STORED IN THE SYSTEM [MW].

Planning Horizon	PP	PBPEF	PBFIS	Optimal Solution
1936-1941	27865.83	29773.74	32299.55	34824.86
1951-1956	24232.82	26817.27	28851.86	38375.47
1971-1976	14329.13	27517.44	26544.69	33470.54
2000-2005	18151.44	21761.86	25847.11	29761.31
LTA	17171.52	25950.09	27437.61	34991.9

intense when the parallel policy and the PBPEF are employed. It may be emphasized that although, during the whole planning horizon, the proposed policy has always presented lower deficit values of energy stored in the system, confirming that this policy needs to use less water to meet the same electric energy market. Additionally, at the end of the planning horizon, we can see that the parallel policy and PBPEF do not get to reach the storage levels obtained by the proposed policy.

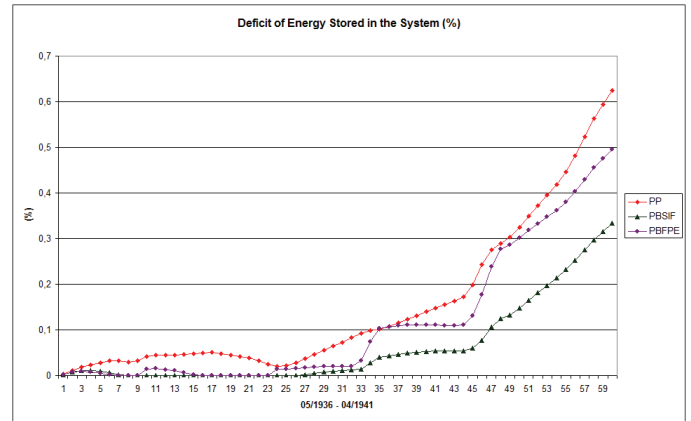


Fig. 8. Trajectories of the deficit of energy stored in the system 1936 to 1941.

Based on the trajectories of deficit of the energy stored in the system, it can be affirmed that, in most case studies accomplished, the simulation of the operation using the proposed policy maximize the hydroelectric benefits of the generation hydrothermal system, as it assists the same market of electric energy, using less water stored in the reservoirs of the plants. Again, at the end of the planning horizon, it is observed that the parallel policy does not get to maintain the close storage levels of the established storage levels for PBFIS and PBPEF. On the contrary, the parallel policy gets to the end of the simulation with more reduced storage levels in the reservoirs, making reliability and the cost of the operation extremely damaged in the continuous operation of the system. Therefore, PBFIS and PBPEF allow the simulation of the hydroelectric system operation to be solid with the continuous operation of the system, since the hydroelectric system does not stop being operated with the end of the planning horizon.

When using the representative operation points of the optimized operation of the reservoirs, the proposed policy (PBFIS) tries to present a differentiated behavior for each reservoir of

plants of hydroelectric system. With the specialization of a fuzzy inference system for each plant, the operation of each one reflects the role that it plays in the hydroelectric system, in agreement with its location in the cascade. Therefore, hydroelectric system is capable of maintaining higher levels of stored energy.

It should be taken into account that the comparisons made with the optimized solution took the optimization with previous knowledge of affluences (optimal absolute), characterizing it as an extremely rigorous pattern. Therefore, the solutions obtained with the simulation model of the operation and the several implemented policies should present a large or smaller degree of sub-optimality.

V. DISCUSSIONS

The proposed operation policy was compared, through some case studies, in the hydroelectric plants of the southeastern Brazilian system, with the policy of parallel operation and with the policy based on functional approximation that uses polynomial and exponential functions. Most results evidenced the efficiency of the proposed policy, taking into account the deficit trajectories and the average of energy stored in the system as parameters. These parameters were obtained by the simulation of the hydroelectric system operation. Regarding the energy stored in the system, the results illustrated that the proposed policy needs less hydraulic resources under the same operation conditions of the parallel policy and PBPEF.

Thus, it is verified that the proposed policy can assure a more reliable and economical supply of the electric power. Economical because the proposed policy needs less hydraulic generation resources than the parallel policy and PBPEF. Reliable because the proposed policy allows the operation of the hydroelectric system with superior storage levels in the reservoirs, reducing the possibility of hydraulic deficits of the hydrothermal generation system. Therefore, the potentiality of the proposed policy can be evidenced in the use of the hydraulic resources turned to electric energy generation.

Additionally, at the end of all planning horizons, it was observed that the parallel policy does not manage to equal the levels of stored energy of the hydroelectric system with the established levels for PBFIS and for PBPEF. Therefore, the proposed policy, besides maximizing the benefits of the generation hydroelectric resources during the planning horizon, still guarantees a larger reliability and a smaller cost of the hydrothermal generation system operation in the continuity of the operation of the hydroelectric system, when arriving at the end of the planning horizon with higher levels of water stored in the reservoirs.

VI. CONCLUSIONS

By the found results, the operation policy based on the Takagi-Sugeno fuzzy inference system establishes a different behavior for the group of reservoirs, so as to maximize the energy stored in the system during the simulation of the hydroelectric system operation. This behavior is obtained through the specific operation for each reservoir, in the agreement with its

position in the cascade. With the predominant influence of the quota effect, the plants whose reservoir volume does not have great influence on the energy stored in the hydroelectric system have emptying priority. On the other hand, the plants whose operative volume of the reservoir has great influence on the system's stored energy present filling priority. As the energy stored in a hydroelectric system is valued by the productivity of the downstream plants, the parameter of the fuzzy rule consequents prioritize higher storage levels in the reservoirs from upstream to downstream in the cascade of plants. Thus, the knowledge of the volume oscillations, in the function of the positioning in the cascade, is represented through the fuzzy production rules.

When opting for a fuzzy inference system to determine the operative volume of each hydroelectric plant, we obtained an action/control strategy that can be monitored and interpreted, even from the language viewpoint. It should be emphasized that, as future works, some improvements can still be investigated in relation to parameters of the fuzzy inference system, mainly in the adjustment of the membership functions, the number of rules and the consequents of the rules employing techniques like Artificial Neural Networks of Genetic Algorithms.

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