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An Energetic Operation Policy Using Fuzzy Controllers for Maximization of Benefits in the Brazilian Hydrothermal Power System

R. A. L. Rabêlo, A. A. F. M. Carneiro, and R. T. V. Braga

***Abstract*—This paper aims to determine an energetic operation policy (EOP) for hydrothermal power systems. In order to determine the EOP, the optimal solution of a deterministic hydrothermal scheduling model was utilized. The EOP was calculated to follow the trajectories obtained by the optimization model. The resulting trajectories were parameterized in terms of the system total energy storage. Using the system energy storage, it is possible to obtain, for each reservoir, the set of points from which a curve can be adjusted using the Takagi-Sugeno Fuzzy Controller. The EOP proposed through the Takagi-Sugeno Fuzzy Controller is used in simulation models to allow comparisons with the adopted EOP in practice in Brazil (parallel policy). As it will be shown in this paper, the proposed EOP using fuzzy controllers maximizes the hydroelectric generation and, as consequence, minimizes the thermoelectric generation cost in the hydrothermal power systems.**

***Index Terms*— Energetic Operation Policy, Fuzzy Controllers, Hydroelectric System, Takagi-Sugeno.**

I. INTRODUCTION

THE introduction of competition in the electric energy industry has an important objective, which consists of obtaining economic efficiency in all segments of the industry. In order to reach this objective, electric energy systems should be modeled efficiently. The search for economic efficiency requires higher risks, which demands detailed procedures for evaluating the performance of systems under more stressed condition, to be taken by the operators than those which were taken in the past [1].

An important task in this process is the energetic operation planning of hydrothermal power systems (EOPHPS). The objective of EOPHPS is to determine a unit generation scheduling that yields an economic and reliable system operation [2]. This problem is quite complex due to various modeling aspects such as the uncertainty of the inflow, interconnection of hydro plants in cascade, nonlinear operational constraints of hydro and thermal units, and the transmission constraints of the electric network [3].

Power generation in the Brazilian electrical power system is provided mainly by hydro plants. Hydro generation, in contrast to thermal generation, results in variable energy availability depending on hydrological conditions and operational policies adopted, although thermal generation furnishes a constant energy availability depending only on its power capacity, usual interruptions for maintenance and forced unavailabilities [4].

The main issue in hydroelectric energy operational planning is the difficulty of handling adequately the stochastic nature of inflows and the individualized representation of hydro power plants [5]. A very common approach has been to aggregate the hydro system into composite reservoirs in order to allow its optimization by stochastic dynamic programming [6, 7]. The main limitation of the composite reservoir approach is that it does not adequately take into account some important aspects of the hydroelectric operation, such as water head effects, hydrological diversity and localized spilling [8]. So, this type of simplification cannot take full advantage of hydraulic resources due to individual characteristics of each plant and existent hydraulic coupling among them are not explicitly considered [1].

An alternative approach consists of using a deterministic optimization tool where an optimal solution with individual hydro representation is obtained for forecasted, historical or synthetic stream flows. On the other hand, a simulation tool can also be useful for energetic operational planning studies, since simulation models allow to evaluate the system operational performance under different energetic operation conditions of inflows and load.

The composite reservoir approach produces an inaccurate representation of hydro production and underestimates spills of systems, especially in large scale hydro systems where the hydrologic diversity is accentuated. To overcome this inaccuracy it is necessary to represent the hydro system in detail, considering individually each hydro plant with its operational constraints and production characteristics. Furthermore, operative interdependence among hydro plants is a consequence of the joint exploitation of hydroelectric resources, through the construction and operation plant and reservoirs located in cascade, in some hydro basins. This way, one plant can affect the operation of another one [9], because

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R. A. L. Rabêlo and A. A. F. M. Carneiro are with the Electrical Engineering Department, University of São Paulo, São Carlos, Brazil (e-mails: ricardor_usp@yahoo.com.br and adriano@sel.eesc.usp.br)

R. T. V. Braga is with the Department of Computing Science, University of São Paulo, São Carlos, Brazil. (e-mail: rtvb@icmc.usp.br).

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the inflow of a downstream reservoir is composed of the water discharge from the upstream reservoirs [10].

This paper applies fuzzy controllers towards the energetic operational planning of the Brazilian hydrothermal system. An energetic operation policy (EOP), using fuzzy controllers, to control the storage of the reservoirs is proposed in order to maximize the hydroelectric generation and, as consequence, minimize the thermoelectric generation cost. A brief presentation concerning energetic operation policy is presented in Section-2. Section-3 introduces the principles of fuzzy controllers. Section-4 briefly discusses the EOP calculation. Section-5 shows many applications of the proposed EOP in comparison with the adopted EOP in Brazil. Section-6 presents the conclusions and highlights the benefits of the proposed EOP.

II. ENERGETIC OPERATION POLICY

An EOP can be defined as a set of rules that establish the way in which reservoirs should operate. An EOP is an important element in operation planning methodology. It is necessary in aggregation procedure for obtaining composite reservoirs as well for establishing release policies in simulation models. Furthermore, an EOP must be adopted to calculate the firm energy of a hydropower system.

So, operation planning methodology in Brazil is highly dependent on EOP. The usual EOP adopted in practice, as for instance in Brazil, is a linear rule (parallel rule or parallel policy) which establishes that all reservoirs must keep the same percent of useful storage. Studies concerning optimal operation of reservoirs for hydroelectric generation have shown that the behavior of each reservoir depends on its location in the cascade. These studies have suggested that parallel policy underestimates the generation capability of hydroelectric systems, especially in the case of highly cascaded systems. Other results indicate that the lower the inflow oscillation range the smaller the necessity of regulation in the system [8]. This means that, for a given hydroelectric cascade, the necessity of regulation could be established *a priori* based on the historical stream flow record. This analysis could define those plants that should always operate as run-of-river plants, those that should always work regulating inflows, and those which eventually could play one or the other role. Furthermore, different constructive characteristics, such as the water storage capacity, plant productivity, waterfall height, etc., and different relative positions in the cascades, are peculiar characteristics of each hydropower plant. This fact practically makes impossible the development of general operational rules [11].

Indeed, to get an efficient EOP can be understood as a way to try to represent the distinctions between the reservoirs, adopting for each reservoir a rule which represents its optimal behavior.

In order to obtain these rules, it is established a relationship between an individual variable of each reservoir – its useful storage in p.u., in the case – and the aggregated state of the system – its stored energy in p.u. Thus, to each state of the system there is a corresponding state for each hydro plant.

In order to determine distinct behavior pattern for each reservoir, the optimal solution of a deterministic hydrothermal scheduling model is utilized [12]. This way, several optimal operations are performed with the hydrothermal system, under the most various hydrologic situations. The results of these optimizations provide sets of points from which may be established the relationship described above.

A curve is fitted over the set of points of each reservoir. Each curve corresponds to an operation rule. As the set of points comes from the optimal operation, it is expected that, at least on average, the curve will contemplate the main aspects of the optimal operation. We have used the Takagi-Sugeno inference system in the fuzzy controller just on the fitting process.

III. FUZZY CONTROLLER

The process of automatic control of a technical process relies mainly on the comparison of desired states of the process with some measured or evaluated states. The controller tries to reach the desired states (set points) by adjustment of the process input values that are identical to the translated output values of the controller. Due to continuous comparison of these values, one gets a closed-loop system. Conventional control strategies use process models or experimental results as a basis for the design of the control strategies. The well-known PID controllers are widely used design paradigms [13]. These controllers use information about the input-output behavior of the process to generate the control action. The behavior of the closed loop is controlled by different gain values that can be adjusted independently by the control engineer.

In control engineering, fuzzy controllers have been extensively-studied [14]. Fuzzy controllers are especial direct digital control systems that use rules to model process knowledge in an explicit way. Instead of designing algorithms that explicitly define the action control as a function of the controller input variables, the designer of a fuzzy controller writes rules that link the input variables with the control variables by terms of linguistic variables [13]. The Figure 1 presents a brief representation of a fuzzy controller.

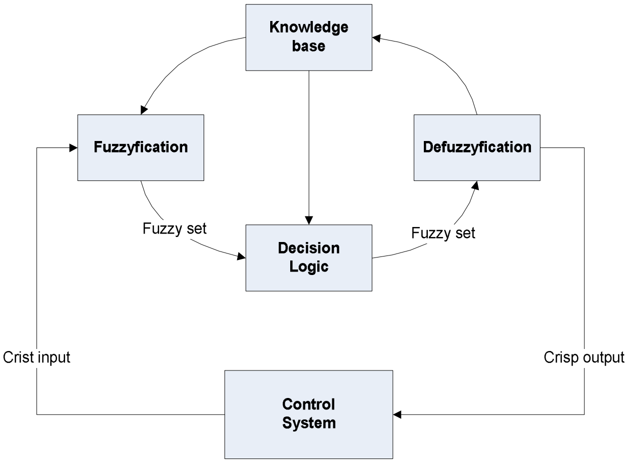

Fig. 1. Representation of a fuzzy controller.

Fuzzyfication is the process of transforming a *crisp value* into a *fuzzy set*. The *knowledge base* contains knowledge about all the input and output fuzzy partitions. It will include the term set and the corresponding membership functions defining the input variables to the fuzzy rule-base system and the output variables, or control actions, to the plant under control. *Decision logic* involves the approximate reasoning and the inference mechanisms. *Defuzzyfication* is the conversion of a fuzzy quantity to a precise quantity, just as fuzzyfication is the conversion of a precise quantity to a fuzzy quantity [15, 16].

Consider, for example, the optimal operation of reservoirs for electric generation. If the water inflows are slightly too high, then storage trajectories of the upstream power plants will present a higher oscillation than storage trajectories using average inflows. Note that the greater the inflow oscillation the deeper the reservoir emptying. Nevertheless, the reservoir reaches the top level at the end of the hydrological year. This behavior is a consequence of the optimal process, which tries to maintain the maximum storage level in the reservoir in order to maximize the electric generation efficiency. If we want to control the influence of the hydrological condition on the behavior of the reservoirs by a fuzzy controller, we interpret the terms "slightly too high" as term of *linguistic variables* and write rules that link these variables. A linguistic variable is a variable whose values are natural language expressions referring to the contextual semantics of the variable [15]. So, a linguistic variable differs from a numerical variable in that its values are not numbers but words as sentences in a natural or artificial language [16, 17].

The idea of Takagi-Sugeno controller is to write rules that have fuzzy antecedents, and crisp consequences that are functions of the input variables. The rule results are aggregated as weighted sums of the control actions corresponding to each rule. The weight of each rule is the degree of membership of the input value in the rule antecedent. Therefore, a defuzzyfication procedure, in this controller, is superfluous.

IV. THE PROPOSED ENERGETIC OPERATION POLICY

In order to determine the energetic operation policy, the optimal solution of a deterministic hydrothermal scheduling model was utilized. Optimal hydrothermal scheduling, investigated by means of a deterministic nonlinear programming problem, can be stated to minimize the operational cost of the system during a given period of time, subject to the water conservation equations and physical constraints, such as limits on storage levels, release, discharge and spillage [3]. This way, an EOP can be calculated to follow the trajectories obtained by the optimization model. For this, resulting trajectories have been parameterized in terms of the system total energy storage. Using the system energy storage, it is possible to obtain, for each reservoir, the set of points from which a rule curve can be adjusted using the Takagi-Sugeno Model.

After all rules have been defined, the control process starts with the computation of all rule-consequences. Then, all active rules are aggregated as weighted sums of the control actions (empty or not the reservoirs, and the level of emptying), which in this case are different values of storage level for each reservoir.

V. APPLICATION

In order to evaluate the performance of the proposed energetic operation policy, it was compared with the parallel policy. Both policies were used in simulation models, so that the energetic operation of the system was evaluated under different conditions of water inflow and load (electric energy market). The simulation of a historical period or of the average inflow may identify how an electrical energy generating system would behave if subjected to certain conditions of operation. It is worth mentioning that the month of May, the beginning of the dry period, has been chosen as the first month of the planning horizon.

A. One Single Hydroelectric Plant

The energetic operation of a hypothetical system with only a single reservoir is simple, as the operator of that system does not need any policy of operation, should only serve the electric energy market. Thus, if the natural tributaries inflow is less than the required inflow to meet the electric energy market, it should empty the reservoir. Otherwise if greater, it should store the excess of this tributary inflow to the maximum.

When, however, there is a cascade system of plants and in parallel, the situation changes completely, because there are several ways to store and empty the reservoirs, each of them with potentially different results. These cascade systems are considered in the case studies of this paper.

B. Two Hydroelectric Plants in Cascade

The system composed of the upstream hydro plant *Emborcação* and the downstream hydro plant *Itumbiara* was chosen for test. Figure 2 shows this test sub-system.

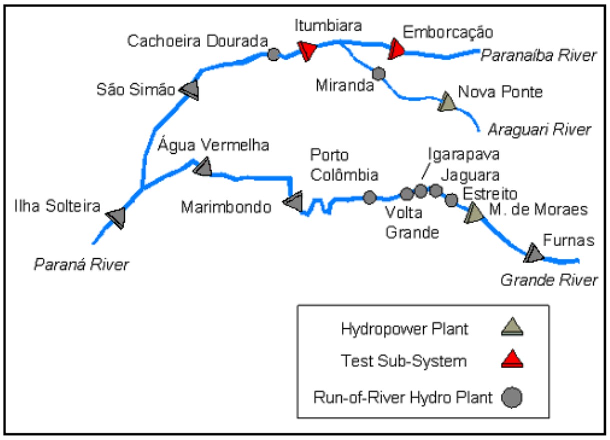

Fig. 2. The first hydroelectric system.

The first system used to evaluate the energetic operation policy consists of two hydroelectric plants of the southeastern Brazil system. The initial storage levels have been established at the maximum, and the planning period embraces five years. The electric energy market (demand) has been considered constant and equal to different percent levels of the total installed capacity. It should be mentioned that these parameters have little effect on the target of this work. Therefore, the greatest influence is given by energetic operation policy. The first application considered the simulation of the hydroelectric system operation for the historical tributaries inflow between 1971 and 1976. To make the comparison between the operation policies, two simulations were made for the same operating conditions. As the operating conditions are identical, the differences in behavior in the energetic operation of the tested system will come exclusively from the operation policies. Figure 3 illustrates a comparison between the trajectories of energy stored in the system by applying the two energetic operation policies. The figure shows the superiority of the fuzzy controllers based operation policy, because the emptying of the reservoirs was much more severe when using the parallel operation policy. This indicates that the parallel operation policy needs more water to meet the same electric energy market under the same operating conditions than the fuzzy controllers based policy.

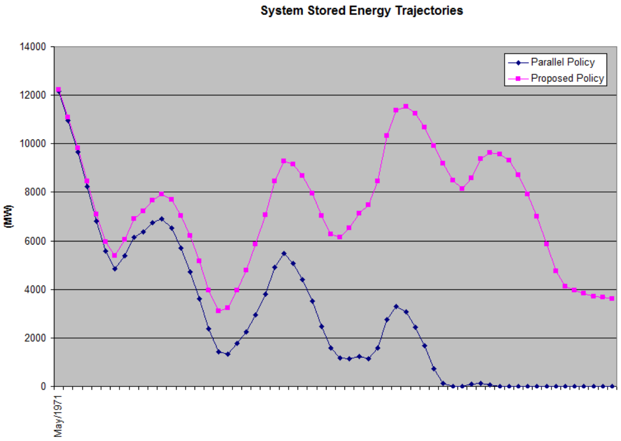

Fig. 3. System stored energy trajectories.

Figure 4 illustrates that proposed energetic operation policy follows the pattern of behavior between the plants in optimized operation, because the upstream plant (*Emborcação*) empties more, regularizing the natural tributaries inflow, while the plant downstream (*Itumbiara*) tends to keep filled with high productivity. For this reason, the parallel policy seems to be an oversimplification modeling [8].

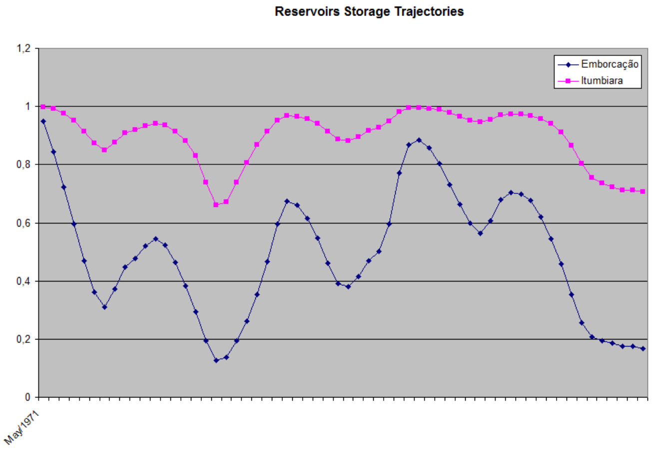

Fig. 4. Reservoirs storage trajectories using the proposed policy.

The second simulation to the comparison between the two operation policies was performed for the historical period between the years 2000 and 2005. Through Figure 5, one can observe the efficiency of operation of the proposed operation policy when compared to the parallel policy. For this simulation the stored energy empties when using the two operation policies. However, the proposed policy has always been more efficient when compared with the parallel policy (Figure 5).

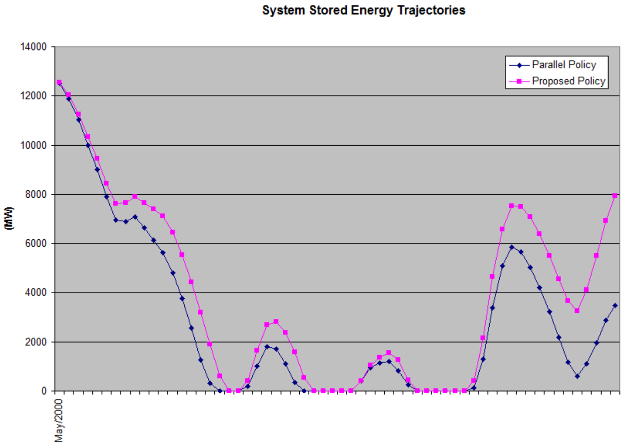

Fig. 5. System stored energy trajectories.

The third simulation performed with the hydroelectric system with tow plants used as tributaries inflow, the long term average (LTA). For Figure 6, one can observe again that the proposed policy can comply with electric energy market by maintaining higher levels of stored energy in the system.

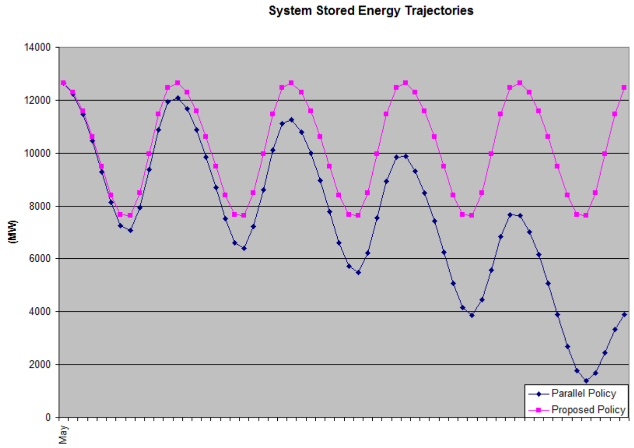

Fig. 6. System stored energy trajectories.

Thus, the proposed energetic operation policy maximizes the benefits of hydroelectric generation resources by making a more optimized use of water stored in reservoirs. It should be noticed that using the proposed policy, the regulation rule has been played by the upstream reservoir (*Emborcação*), while the downstream one has almost worked as a run-off-river plant (Figure 7). Furthermore, using the proposed energetic operation policy, the reservoirs reach the top level at the end of hydrological year. However, the parallel policy is not able of filling up the reservoirs (Figure 8). Therefore, the proposed policy maximizes the electric generation efficiency.

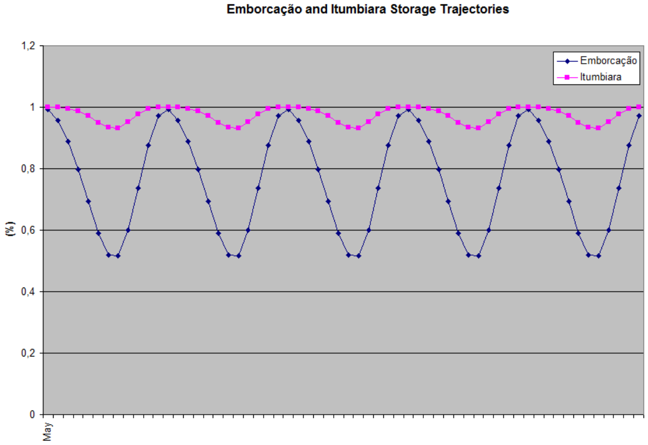

Fig. 7. Reservoirs storage trajectories using the proposed policy.

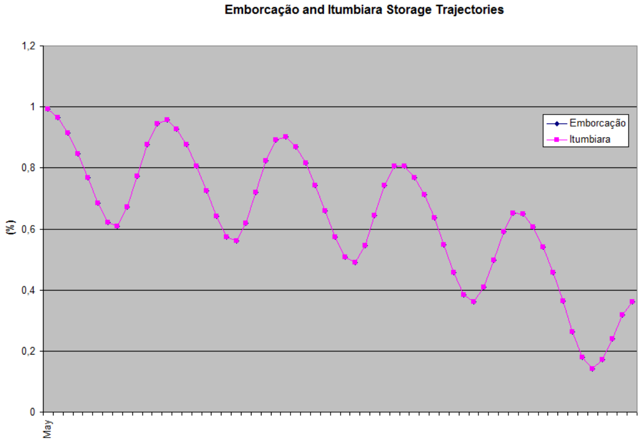

Fig. 8. Reservoirs storage trajectories using the parallel policy.

C. *Seven Hydroelectric Plants in Cascade*

At this point, the energetic operation policy will be applied to the seven plants hydroelectric system shown in Figure 9.

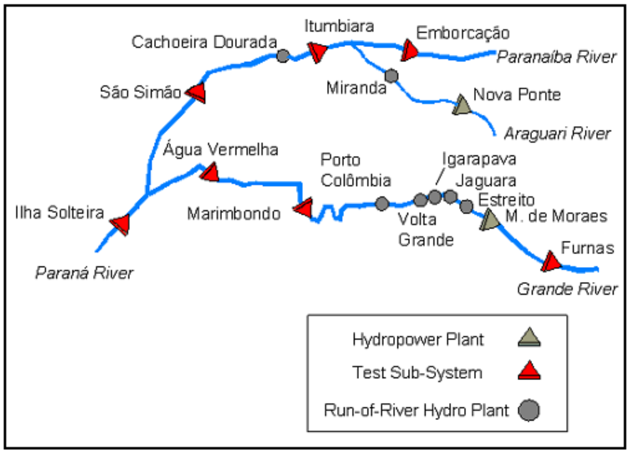

Fig. 9. The last hydroelectric system.

The final system used for implementation of the energetic operation policy is composed of seven hydroelectric plants of the southeast Brazil system. For this seven hydroelectric plants system, it is considered the same operating conditions used in the first hydroelectric system (planning period, electric energy market, etc.). The first application considered the simulation of the hydroelectric system operation using the historical tributaries inflow between 1971 and 1976. To accomplish the comparison between the policies of operation, two simulations are made for the same operating conditions. Figure 10 shows the trajectories of four of the seven hydroelectric power plants, using the proposed policy.

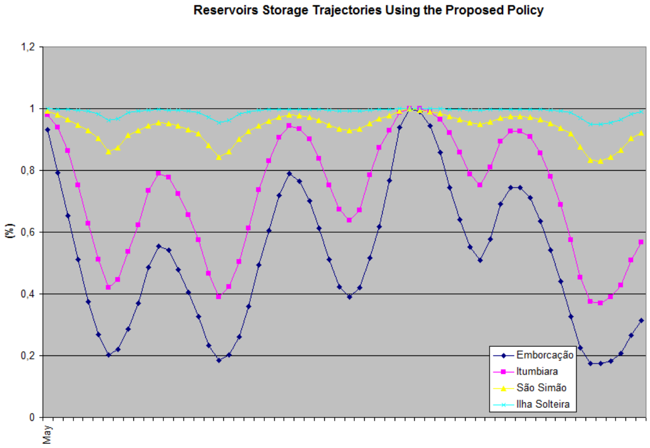

Fig. 10. Reservoirs storage trajectories using the proposed policy.

This test shows that using the proposed energetic operation policy, reservoirs play a completely different role in the system, depending on their relative position in the cascade. The regulation role has mainly been played by the upstream reservoirs, while the downstream ones have been played as almost a run-of-river plant. It should also be observed that using the parallel policy, all reservoirs keep the same percent of useful storage. Furthermore, the produced trajectories using the proposed EOP follow the principles of optimal reservoirs operation for electric generation, once the proposed EOP establishes that the behavior of each reservoir depends on its location in the cascade. Therefore, the proposed EOP maximizes the benefits in hydrothermal power systems.

The efficiency of the downstream power plants affects water in both reservoirs while the efficiency of the upstream power plants only affects water in the upstream reservoir. Thus, the regulation role, which reduces generation efficiency, should be played by the upstream reservoir in order to better take advantage of hydraulic resources [8].

To prove the efficiency in the use of hydroelectric generation resources by proposed operation policy, the Figure 11 should be checked. This figure illustrates the comparison of the trajectories of stored energy in the system using the two policies. As it can be seen, the proposed EOP maintains greater storage level than parallel policy in order to maximize the electric generation efficiency.

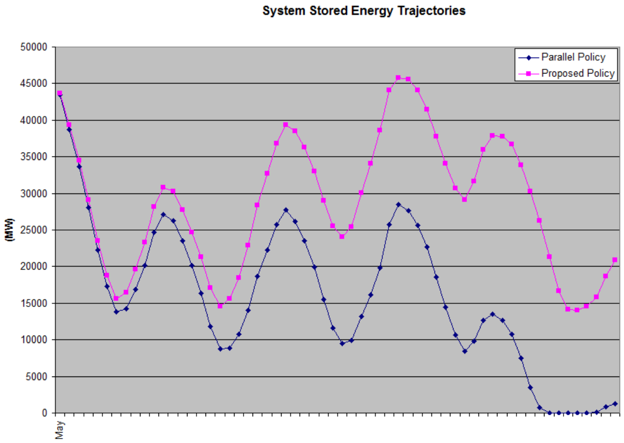

Fig. 11. System stored energy trajectories.

The second simulation using the cascade of seven hydroelectric power plants is carried out for the historical period between the years 2000 and 2005. By Figure 12, one can observe the efficiency of the proposed operation policy when compared to the parallel policy. For this simulation, it can again observe a emptying of the stored energy when using the two policies of operation, however; once again, the fuzzy controller proposed policy has higher levels of the storage reservoir when compared with the parallel policy.

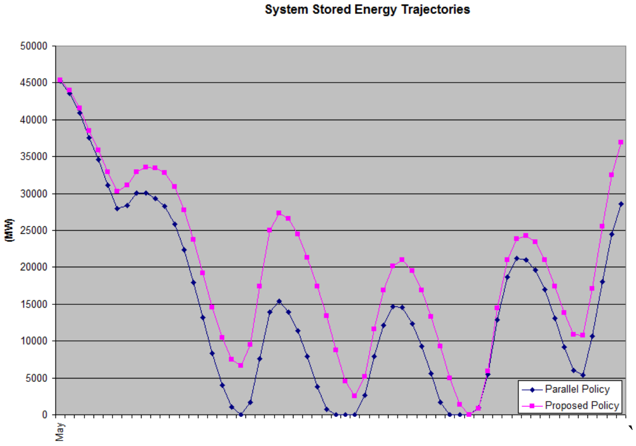

Fig. 12. System stored energy trajectories.

The stored energy in a plant is assessed by the productivity of all its downstream plants. The height of drop of the power plant further downstream, for example, affects the stored energy of all the plants of the cascade. Thus, the optimized operation prioritizes the upstream emptying and filling in the opposite direction. Figure 13 illustrates that the proposed energetic operation policy follows this important principle of optimized operation.

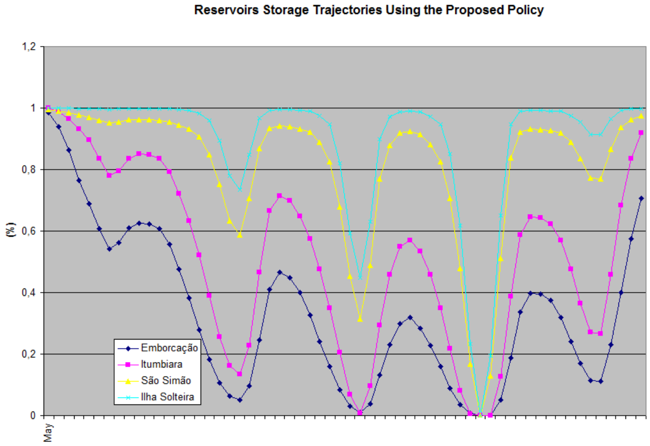

Fig. 13. Reservoirs storage trajectories using the proposed policy.

VI. CONCLUSIONS

This paper proposes an energetic operation policy using fuzzy controllers for maximizing the benefits of hydraulic resources for electric generation in hydrothermal power systems.

The EOP was compared with the parallel policy adopted in practice in Brazil. Several results above show a saving of hydraulic resources on supply of electric energy market, providing an improvement in hydro generation and as result, minimizing the thermoelectric generation cost. This can be concluded not solely by the higher values of the system total energy storage, but also by different behaviors of the reservoirs, which are in accord to the optimal operation of reservoir for electric generation. Therefore, we can guarantee that the proposed EOP maximizes the benefits of the water resources in hydrothermal power systems. It is worth mentioning that the obtained EOP can also be used to develop or to improve a general composite representation of a hydroelectric system that allows the use of stochastic dynamic programming in hydrothermal operation planning.

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

Ricardo de Andrade Lira Rabêlo was born in Piauí in Brazil. He received a B.Sc degree in Computer Science from Federal University of Piauí, Teresina. He is pursuing the D.Sc. degree in electrical engineering from the Electrical Engineering Department, São Carlos Engineering School, University of São Paulo, São Paulo, Brazil. His areas of research interest are electric energy systems operation planning, energetic operation policies for reservoirs, fuzzy systems, artificial neural networks, software engineering, and nonlinear programming.

Adriano Alber de França Mendes Carneiro was born in Brazil 1944. He received a B.Sc. degree in electrical engineering from the Catholic University of São Paulo, São Paulo, Brazil, a M.Sc. degree in power systems from the Federal School of Engineering of Itajubá, Itajubá, Brazil, and a D.Sc. degree in operation planning of power systems from the State University of Campinas, Brazil. He is currently an Assistant Professor with the Electrical Engineering Department, São Carlos Engineering School, University of São Paulo, São Carlos, Brazil. His area of research is planning and operations of electric energy systems.

Rosana Teresinha Vaccare Braga was born in São Paulo (Brazil), 1965. She is a Professor at ICMC -- University of São Paulo - Brazil, where she also received a D.Sc. in 2003, and a M.Sc degree in 1998, and a B.Sc degree in Computer Science in 1986. She has worked with business systems development from 1986 to 1996. Her research activity is in Software Engineering (Product Lines, Frameworks, Pattern Languages, Aspect-oriented Programming, Reengineering, and Reverse Engineering).