AN APPROACH TO CONSIDER HYDRAULIC COUPLED SYSTEMS IN THE CONSTRUCTION OF EQUIVALENT RESERVOIR MODEL IN HYDROTHERMAL OPERATION PLANNING

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Abstract – Coordinating the operation of large hydrothermal generating systems, such as the Brazilian system is a very complex task. Usually, the operation planning problem is divided in linked subproblems according to decision horizons. These horizons varies from long-term scheduling (1 to 5 years ahead) up to the short-term scheduling and dispatch. To keep the solution of the long-term operation planning problem computationally tractable, it is necessary to introduce simplifications to the original problem. One important approximation is the aggregation of reservoirs into equivalent energy reservoirs. However, the currently available methodology to construct Equivalent Energy Models is only able to represent subsystems without hydraulic coupling. The objective of this paper is to derive a methodology to construct the Equivalent Energy Model that allows dealing with systems hydraulically coupled. The methodology is applied to a configuration of the Brazilian generating system.

Keywords: hydro generation, equivalent reservoir model, multireservoirs system

1 INTRODUCTION

The Brazilian generating system is hydro dominated, accounting for more than 90% of the produced electrical energy. This large scale hydro system is characterized by large reservoirs presenting multi-year regulation capability, arranged in complex cascades over several river basins, including the world's largest hydroplant, Itaipu, with 12600 MW installed capacity and jointly owned by Paraguay. Additionally, the availability of limited amounts of hydroelectric energy, in the form of stored water in the system reservoirs, in conjunction the variability of future inflows, creates a link between the operation decision in a given stage and future consequences of the decision.

Therefore, coordinating the operation of such a system is a very complex task posed to the planners. Usually, the operation planning problem is divided in linked subproblems according to decision horizons [1]. These horizons varies from long-term scheduling (1 to 10 years ahead) where long lasting drought and their associated probabilities of occurrence as well multiyear regulation capability are analyzed, up to the short-term scheduling and dispatch. Specialized algorithms have been developed to each one of the decision horizons [1]. In Brazil, the Independent System Operator (ONS) and the Whole Sale Energy Market (CCEE) use a chain of models for the hydrothermal coordination and to determine the spot price [1]. In particular, in the long-term operation planning a computational model called NEWAVE is used [2]. This model is based on dual stochastic dynamic programming [3]; it is also able to evaluate the performance of the generating system in meeting the load through probabilistic indices.

To keep the solution of the long-term operation planning problem computationally tractable, it is necessary to introduce simplifications to the original problem. One important approximation is the aggregation of system reservoirs into equivalent energy reservoirs models. For example, the four main Brazilian subsystems (North, Northeast, South and Southeast/Central West) are approximated into four equivalent energy models, which are electrically connected through the existing main interconnection lines. This representation is illustrated in Figure 1.

However, the original methodology to construct the Equivalent Energy [4] is only able to represent subsystems without hydraulic coupling. In other words, a river basin should contain hydro power plants that belong to only one subsystem; it fails in the case that part of the hydro plants belongs to one subsystem and the remaining belongs to another one.

The objective of this paper is to extend the methodology to construct the Equivalent Energy Model to allow dealing with subsystems hydraulically coupled. In this case, the operation of a specific subsystem will also depend on the operation of upstream subsystems.

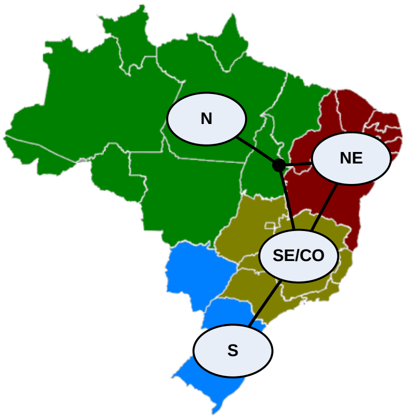

Figure 1 The four main Brazilian subsystems.

The proposed approach is illustrated in a case study with a configuration of the Brazilian generating system. Initially, the Itaipu power plant is modeled in the Southeast/Central subsystem not taking into account the ±600 kV HVDC link and the 765 kV AC transmission line that links Itaipu power plant to South and Southeast/Central West systems. After, Itaipu power plant will be represented as a subsystem itself, allowing that the transmission constraints could be represented, but at this time, the operation of Itaipu subsystem will depend on the operation of the Southeast/Central West subsystem once part of the discharge of this last subsystem is inflow to the former. In turn, the operation of Itaipu subsystem will impact the operation of the other systems.

2 THE CONCEPTS OF EQUIVALENT RESERVOIR AND THE ENERGY INFLOW MODEL

Because the sum of hydroelectric generation and thermal generation should match the total energy load, the system operation cost, given by the fuel of the thermal units, can be considered to be a function of the total hydro generation rather than the vector of individual hydro releases. This suggests the use of some aggregate representation of the hydroelectric system as a state variable. Furthermore, because the potential for energy production of stored water in a hydro system depends on the total developed plant head downstream of each hydro plant, the aggregated storage capacity of the subsystem should be expressed in terms of its content rather than its stored water volume.

The aggregation technique, known as equivalent reservoir representation, is based on the estimation of the energy produced by the complete depletion of the subsystem reservoirs for a given set of initial storage. If there is only one reservoir, the energy produced by the depletion of a volume Δv of stored water is a function of its gravitational potential energy, (1):

$$\Delta E = \rho\, h(v)\, \Delta v \qquad (1)$$

where

ΔE is the generated energy (MWh)

ρ is the plant productivity factor (gravitational constant times turbine/generator efficiency)

$h(v)$ is the reservoir head which depends on the stored volume v

The energy produced by the complete depletion of the reservoir from its maximum volume $\bar{v}$ is thus given by (2):

$$\overline{SE} = \int_0^{\bar{v}} p\, h(v)\, dv \qquad (2)$$

Suppose now that we have two reservoirs in series, as illustrated in Figure 2. Since a water volume Δv_1 released from upper reservoir 1 will also be used to generate energy at plant 2, the energy produced is given by (3):

$$\Delta E_1 = (p_1\, h_1(v_1) + p_2\, h_2(v_2))\, \Delta v_1 \qquad (3)$$

Because the energy produced by reservoir 1 depends on the head of reservoir 2, the subsystem stored energy will depend on how both reservoirs are depleted. In other words, the total energy produced will depend on the system operating rules [5]. In the construction of the aggregate reservoir for the Brazilian system, some simplified operation rules that approximate the actual depletion policy of the system reservoirs were used. The experience shows that, in practice, the operator of the system aim to maintain all the reservoirs at the same level. That is, the parallel operating policy hypothesis is reasonable.

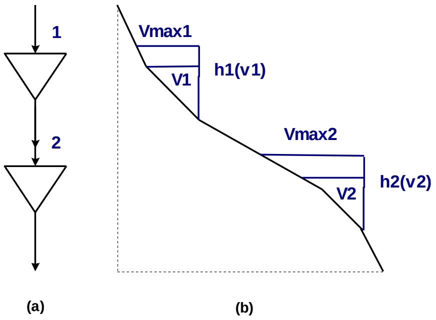

Figure 2 Representation of two reservoirs in series: (a) schematic diagram; (b) side view.

Different equivalent reservoirs were built for each Brazilian region. The accuracy of the aggregate models can be validated against simulation models that represent in detail the operation of the individual hydroelectric plants and their effect on units downstream [6].

2.1 The Aggregate System Model

The equivalent reservoir model is a composite representation for the multireservoir hydroelectric power system. This is a reservoir which receives, instead of water, stores and releases potential energy.

The major components of the aggregate system model are represented in Figure 3.

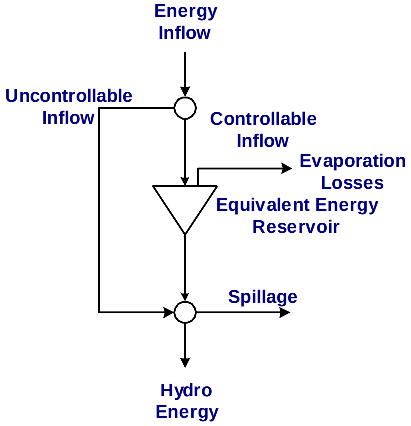

Figure 3 Aggregate System Model

The total energy inflow to the equivalent reservoir is divided in two parts:

- *Controllable energy inflow*, which represents the inflow volumes that can be stored in the subsystem reservoir;
- *Uncontrollable energy inflow*, which represents lateral inflow volumes arriving at run-of-the-river plants, which have no associated reservoir.

The energy outflow from the equivalent reservoir and the controllable inflow are limited by the capacity of the subsystem turbine/generator sets. Energy flow volumes exceeding these limits are spilled, that is, cannot be used for hydro production. Each of the aggregate subsystem components will be defined in the next item.

3 OUTLINE OF THE PROPOSED APPROACH

3.1 The Equivalent Reservoir Model

The maximum energy that can be stored in the equivalent energy reservoir is estimated as the energy produced by the complete depletion of the system reservoirs, that is, as the maximum capacity of each reservoir multiplied by its productivity plus that of all hydroplants downstream this reservoir, given by (4):

$$EARM_{max} = \sum_{i \in R} Vutil_i \left(\rho_i \bar{h}_i + \sum_{j \in H_i} \rho_j \bar{h}_j \right) \tag{4}$$

where

R is the set of reservoirs of the system

$Vutil_i$ is the maximum stored volume of reservoir i

$\bar{h}_i$ is the average head of reservoir i or the head (constant) of run-of-the-river plant i

H_i is the set of reservoirs and run-of-the-river plants downstream of reservoir i

For easy explanation, the equation associated with the consideration of hydro coupling in the Equivalent Reservoir Model will be initially derived by using a simple example. Then the equations are generalized.

Consider the hydrosystem Y, depicted in Figure 4, which is composed by four reservoirs and one run-of-the river plant.

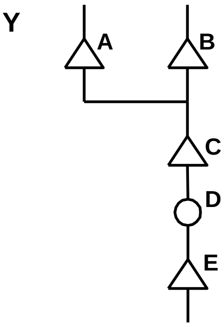

Figure 4 Hydro system Y

Now consider that this system is split into two subsystems Y_1 and Y_2, which are clearly coupled, as shown in Figure 5.

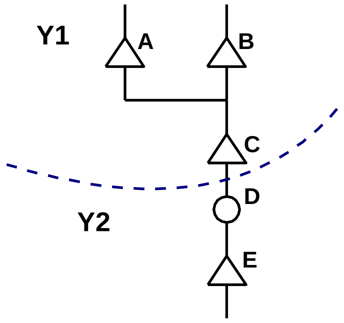

Figure 5 Hydro subsystems Y_1 and Y_2

The maximum energy that can be stored in the system Y is given by (5):

$$\begin{aligned} EAMAX\,(Y) = {} & Vutil_A(\rho_A \bar{h}_A + \rho_C \bar{h}_C + \\ & \rho_D \bar{h}_D + \rho_E \bar{h}_E) + Vutil_B(\rho_B \bar{h}_B + \rho_C \bar{h}_C + \\ & \rho_D \bar{h}_D + \rho_E \bar{h}_E) + Vutil_C(\rho_C \bar{h}_C + \rho_D \bar{h}_D + \\ & \rho_E \bar{h}_E) + Vutil_E\, \rho_E \bar{h}_E \end{aligned} \tag{5}$$

In the same way, the maximum energies that can be stored in the subsystems Y_1 and Y_2 respectively are given by (6) and (7):

$$\begin{aligned} EAMAX\,(Y_1) = {} & Vutil_A(\rho_A \bar{h}_A + \rho_C \bar{h}_C + \\ & \rho_D \bar{h}_D + \rho_E \bar{h}_E) + Vutil_B(\rho_B \bar{h}_B + \rho_C \bar{h}_C + \\ & \rho_D \bar{h}_D + \rho_E \bar{h}_E) + Vutil_C(\rho_C \bar{h}_C + \rho_D \bar{h}_D + \\ & \rho_E \bar{h}_E) \end{aligned} \tag{6}$$

$$EAMAX\,(Y_2) = Vutil_E\, \rho_E \bar{h}_E \tag{7}$$

Comparing the expressions (5) to (7), it can be seen that:

- the sum of $EARM_{max}(Y_1)$ and $EARM_{max}(Y_2)$ results in $EARM_{max}(Y)$;
- part of the energy stored in subsystem Y_1 will be generated in subsystem Y_1 itself;
- part of the energy stored in subsystem Y_1 belongs to subsystem Y_2, downstream of Y_1;
- the complement to the energy stored in subsystem Y_1 will be generated in subsystem Y_2.

In this way, it can be stated about a release of certain amount from subsystem Y_1:

- just a part of the release will imply in generation in subsystem Y_1;
- another part of the release will be generated in the run-of-the-river plant of subsystem Y_2;
- the complement to the release will be controlled by the reservoir of subsystem Y_2.

In the example, the amount of the maximum stored energy that can be generated in the subsystem Y_1 itself, is given by (8):

$$\begin{aligned} & Vutil_A(\rho_A \bar{h}_A + \rho_C \bar{h}_C) + Vutil_B(\rho_B \bar{h}_B + \\ & \rho_C \bar{h}_C) + Vutil_C(\rho_C \bar{h}_C) \end{aligned} \tag{8}$$

The amount of the maximum stored energy that will result in uncontrollable inflow to subsystem Y_2, is given by (9):

$$\begin{aligned} & Vutil_A(\rho_D \bar{h}_D) + Vutil_B(\rho_D \bar{h}_D) + \\ & Vutil_C(\rho_D \bar{h}_D) \end{aligned} \tag{9}$$

The amount of the maximum stored energy that will result in controllable inflow to subsystem Y_2, is illustrated in (10):

$$\begin{aligned} & Vutil_A(\rho_E \bar{h}_E) + Vutil_B(\rho_E \bar{h}_E) + \\ & Vutil_C(\rho_E \bar{h}_E) \end{aligned} \tag{10}$$

Generalizing, the amount of the maximum stored energy that belongs to the subsystem itself is shown in (11):

$$\sum_{i\in R} Vutil_i \left(\rho_i \, \bar{h}_i + \sum_{j\in J_i^a} \rho_j \, \bar{h}_j \right) \tag{11}$$

where

J_i^a is the set of reservoirs and run-of-the-river plants downstream of reservoir *i*, belonging to the subsystem itself.

The amount of the maximum stored energy that will result in controllable inflow to downstream systems is given by (12):

$$\sum_{i\in R} Vutil_i \left(\sum_{j\in J_i^b} \rho_j \, \bar{h}_j \right) \tag{12}$$

where

J_i^b is the set of reservoirs and run-of-the-river plants starting from the first reservoir downstream of reservoir *i*, belonging to the downstream subsystems.

The amount of the maximum stored energy that will result in uncontrollable inflow to downstream subsystems is shown in (13):

$$\sum_{i\in R} Vutil_i \left(\sum_{j\in J_i^c} \rho_j \, \bar{h}_j \right) \tag{13}$$

where

J_i^c is the set of consecutive run-of-the-river plants downstream of reservoir *i* until the first reservoir, belonging to the downstream subsystems.

These quantities, when divided by the maximum stored energy, can be interpreted as weight up coefficients of the release of a subsystem, in the construction of an energy dispatch problem, as presented in [2].

$$A = \frac{\sum_{i\in R} Vutil_i \left(\rho_i \, \bar{h}_i + \sum_{j\in J_i^a} \rho_j \, \bar{h}_j \right)}{\sum_{i\in R} Vutil_i \left(\rho_i \, \bar{h}_i + \sum_{j\in J_i} \rho_j \, \bar{h}_j \right)} \tag{14}$$

where

J_i is the set of reservoirs and run-of-the-river plants downstream of reservoir *i*.

$$B = \frac{\sum_{i\in R} Vutil_i \left(\rho_i \, \bar{h}_i + \sum_{j\in J_i^b} \rho_j \, \bar{h}_j \right)}{\sum_{i\in R} Vutil_i \left(\rho_i \, \bar{h}_i + \sum_{j\in J_i} \rho_j \, \bar{h}_j \right)} \tag{15}$$

$$C = \frac{\sum_{i\in R} Vutil_i \left(\rho_i \, \bar{h}_i + \sum_{j\in J_i^c} \rho_j \, \bar{h}_j \right)}{\sum_{i\in R} Vutil_i \left(\rho_i \, \bar{h}_i + \sum_{j\in J_i} \rho_j \, \bar{h}_j \right)} \tag{16}$$

3.2 *The Energy Inflow*

The controllable energy inflow is estimated as the total inflow arriving at each reservoir multiplied by its productivity plus that of any run-of-the-river plants between it and the next downstream reservoir, is given by (14):

$$CE = \sum_{i\in R} QI_i \left(\rho_i \, \bar{h}_i + \sum_{j\in H_i} \rho_j \, \bar{h}_j \right) \tag{17}$$

where

QI_i is the incremental inflow volume at reservoir *i*, that is, the difference between the inflow volume at reservoir *i* and the inflow volumes at reservoirs immediately upstream.

The uncontrollable energy inflow corresponds to the uncontrollable inflow volume arriving at each run-of-the-river plant multiplied by its productivity. The uncontrollable energy inflow is limited by the maximum generation/turbine outflow at each plant, as illustrated in (15).

$$UE = \sum_{j\in F} Min \left\{ UQ_j , \bar{Q}_j \right\} \rho_j \, \bar{h}_j \tag{18}$$

where

F	is the set of run-of-the-river plants of the subsystem
UQ_j	is the uncontrollable inflow volume arriving at plant *j*
Q_j	is the total flow arriving at plant *j*
R_j	is the set of reservoirs immediately upstream of plant *j*
$\bar{Q}_j$	is the maximum generator/turbine outflow of plant *j*

3.3 *Correction of Controllable Inflow*

Since the controllable energy was calculated using average heads, $\bar{h}_i$, it is necessary to correct it during simulation or optimization to take into account the effect of head variation. A correction curve is fitted based on calculation of the controllable energy for different values of the stored energy in the reservoir, as shown in Figure 6.

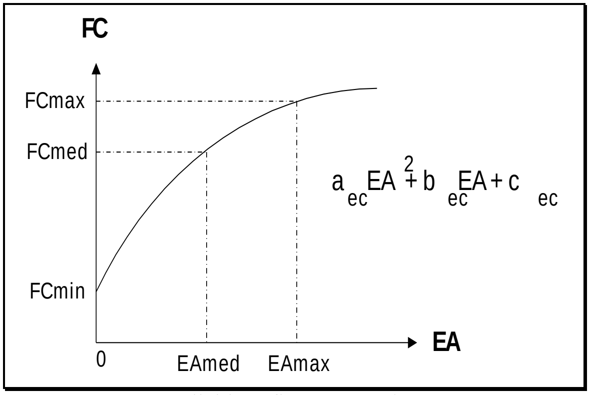

Figure 6 – Controllable Inflow Correction Curve

Each point of the curve can be calculated as equation (19):

$$FC(h)=\frac{\sum_{n=1}^{NSH}\sum_{i\in R} QI_{i,n}\left(\rho_i\, h_i+\sum_{j\in H_i}\rho_j\, h_j\right)}{\sum_{n=1}^{NSH}\sum_{i\in R} QI_{i,n}\left(\rho_i\, \bar{h}_i+\sum_{j\in H_i}\rho_j\, \bar{h}_i\right)} \qquad (19)$$

where

NSH	number of values in the historical record of water inflows
h	is the maximum (minimum or average) head of reservoir or the head (constant) of run-of-the-river plant if the plant belongs to the subsystem; is the average head of reservoir *i* or the head (constant) of run-of-the-river plant *i* if the plant belongs to downstream systems.

Similar development will make to minimum outflow energy.

4 THE OPERATION DISPATCH PROBLEM

In the NEWAVE model, the long term operation planning problem is represented as a multi stage stochastic linear programming problem [SLP]. The objective is to minimize the expected value of the operation cost during the planning period (*t=1* to *t=T*), given a known initial state of the system. Fuel costs and penalties for failure in load supply compose the operation cost. The multi stage stochastic linear programming problem is described in [2]. A simplified version of this problem [8], already considering coupled subsystems and applying the weight up coefficients described in section 3.1, is described as:

$$\alpha_t(x_t)=\underset{EAF_t|x_t}{E}\left(\min\sum_{k\in NS}\sum_{j\in NUT_k} CT_j GT_{t,j}+\frac{1}{1+\beta}\alpha_{t+1}(x_{t+1})\right)$$

for $t = 1, \dots, T$ (20)

subject to

Storage balance equation in each system aggregated reservoir k

$$EA_{t+1}(k)=EA_t(k)+FC_t(k)\,CE_t(k)-$$
$$GH_t(k)-EVT_t(k)+B(l,k)GH_t(l) \qquad k=1,\cdots NS$$

(20a)

Load supply equation in each system k and for each load level

$$A(k)GH_t(k)+\sum_{j\in NUT_k} GT_{t,j}+\sum_{i\in\theta_k}(F_{t,}(i,k)-F_{t,}(k,i)+$$
$$+DEF_t(k)-EXC_t(k)=D_t(k)\ -UE_t(k)-$$
$$-C(l,k)GH_t(l) \qquad k=1,\dots,NS$$

(20b)

Maximum turbined outflow in each system aggregated reservoir k

$$A(k)GH_t(k)+UE_t(k)+C(l,k)GH_t(l)\le GHMAX_t(k)$$
$$k=1,\dots,NS$$

(20c)

Bounds in storage in each system aggregated reservoir

$$EAMIN_{t+1}(k)\le EA_{t+1}(k)\le EAMAX_{t+1}(k) \qquad k=1,\dots,NS$$

(20d)

Maximum generation in each thermal plant j

$$0\le GT_{t,j}\le \overline{GT}_{t,j} \qquad \forall j\in NUT_k,\ k=1,\dots,NS$$

(20e)

Flow limits among systems

$$\left|F_t(i,k)\right|\le \bar{F}_t(i,k) \qquad i=1,\dots,NS \quad k=1,\dots NS$$

(20f)

Flow limits among systems without load and plants

$$\sum_{i\in\theta_k}(F_t(j,k)-F_t(k,j))=0 \qquad k=1,\dots,NFIC$$

(20g)

Set of multivariate linear constraints (Bender´s cut) representing the cost-to-go function

$$\alpha_{t+1}-\sum_{k\in NS}\bar{\pi}_{EA_{1,t+1}(k)}\,EA_{t+1}(k)+$$
$$\sum_{j=1}^{p}\bar{\pi}_{EAF_{1,j,t+1}(k)}EAF_{t-j+1}(k)\ge\bar{\delta}_{1,t+1}$$
$$\vdots$$
$$\alpha_{t+1}-\sum_{k\in NS}\bar{\pi}_{EA_{q,t+1}(k)}\,EA_{t+1}(k)+$$
$$\sum_{j=1}^{p}\bar{\pi}_{EAF_{q,j,t+1}(k)}EAF_{t-j+1}(k)\ge\bar{\delta}_{q,t+1}$$

(20h)

where

x_t	State vector at the beginning of stage *t* composed by EA_t and $(EAF_{t-1}, \dots, EAF_{t-p})$
$\alpha_t(x_t)$	Expected value of total operation cost from stage *t* to end of planning period *T*, also called expected cost-to-go function of stage *t*;
β	Discount rate;
$A(k)$	The quantity of the stored energy of system *k* that belongs to the subsystem itself
$B(l,k)$	The quantity of the stored energy of system *l* that will result in controllable inflow to downstream systems, k
$C(l,k)$	The quantity of the stored energy of system *l* that will result in uncontrollable inflow to downstream systems, k
$EA_t(k)$	Storage energy of system *k* in the beginning of stage *t*;
$EAMAX_t(k)$	Maximum storage energy of system *k* in the beginning of stage *t*;
$GH_t(k)$	Controllable hydro production of system *k*;
$GHMAX_t(k)$	Maximum hydro production of system *k*;
$EVT_t(k)$	Spillage energy of system *k*;
$EXC_t(k)$	Energy excess due to uncontrollable energy and/or minimum outflow energy and/or minimum thermal generation on system *k*;
$CE_t(k)$	Controllable energy inflow plus minimum outflow energy of system *k*;

$UE_t(k)$	Uncontrollable energy inflow of system k; represents lateral inflow volumes arriving at run-of-the-river hydro plants;
$EAF_t(k)$	Energy inflow volume of system k; $CE_t(k)+UE_t(k)$; $CE_t(k)=a\,EAF_t(k)$; $UE_t(k)=(1\text{-}a)\,EAF_t(k)$
$GT_{t,j}$	Thermal generation of plant j;
$\overline{GT}_{t,j}$	Maximum thermal generation;
$F_t(i,k)$	Energy flow from system i to system k;
$\overline{F}_t(i,k)$	Energy flow limit from system i to system k;
$D_t(k)$	Demand of system k;
$DEF_t(k)$	Energy not supplied in system k;
CT_j	Generation cost of thermal plant j;
$EAMIN_t(k)$	Minimum limit on storage energy;
$FC_t(k)$	Controllable energy's correction factor; it is a function of storage energy at the beginning of the stage;
θ_i	Set of systems directly connected to system i;
NS	Number of systems;
$NFIC$	Number of systems without generation and load;
NUT_k	Number of thermal plants of system k;
q	Number of constraints of the expected cost-to-go function;
$\overline{\pi}_{EA_{l,t+1}}(k)$	Simplex multiplier or dual variable associated to energy storage level;
$\overline{\pi}_{EAF_{l,1,t+1}}(k)$	Simplex multiplier or dual variable associated to energy inflow in the previous stage;
$\delta_{l,t+1}$	Cost-to-go function RHS.

5 CASE STUDY

The application of the methodology will be illustrated with a configuration of the Brazilian generating system used in the monthly operation plan conducted by ONS [2]. A hundred and thirty hydro plants and a hundred thermal plants compose the plan. The Brazilian electrical system is represented by four subsystems: South (S), Southeast/Central West (SE/CO), North (N) and Northeast (NE). Itaipu is a huge power plant located at the end of the cascade in Paraná River. Nowadays, this plant is modeled as belonging to the Southeast/Central subsystem. The Case 1 adopts this configuration and its topology is illustrated in Figure 1.

In order to explicit considerate the interconnection of the Itaipu power plant with the subsystems South and Southeast/Central West through the ±600 kV HVDC link and the 765 kV transmission line, SE/CO subsystem was split into three subsystems: Southeast/Central West (SE/CO), Itaipu (IT) and Paraná (PR). Itaipu power plant was removed from the original SE/CO subsystem, to constitute a new subsystem (IT). All hydro plants that belong to Parana basin, which is hydrologic coupled with Itaipu power plant, now constitute a new subsystem called PR subsystem. The hydro plants that have no hydrologic coupling with Itaipu power plant remain at the original SE/CO subsystem. PR subsystem does not have load and neither interchange constraints with SE/CO. The topology used in Case 2 is illustrated in Figure 7. It shows the electrical interconnections (bold lines) between the six subsystems and the hydrologic coupling (arrow) between IT and PR subsystems.

In this way, the operation of Itaipu subsystem depends on the operation of the Paraná subsystem once part of the discharge of this last subsystem is inflow to the former subsystem. In turn, the operation of Itaipu subsystem impacts the operation of the other subsystems.

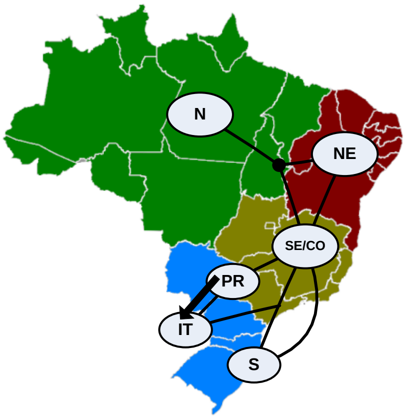

Figure 7 Topology of Case 2.

Figure 8 shows the expected value of energy inflows for each month. It could be noted that sum of energies of SE/CO, IT and PR subsystems for Case 2 is the same of SE/CO subsystem in Case 1. This result is a condition in the proposed methodology because no inflow energy is created nor eliminated.

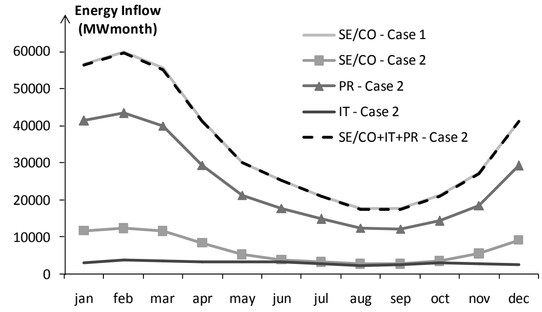

Figure 8 Expected value of the energy inflow sequence.

The optimal operation policies for Cases 1 and 2 have been constructed using NEWAVE model, based on November/2010 monthly operation plan. Then, the optimal operation policies were simulated considering 2000 synthetic scenarios of energy inflows and a five years planning horizon.

Figure 9 presents the expected value of total operational costs. Note that Case 2 is more expensive than Case 1 because its operation is more restrictive.

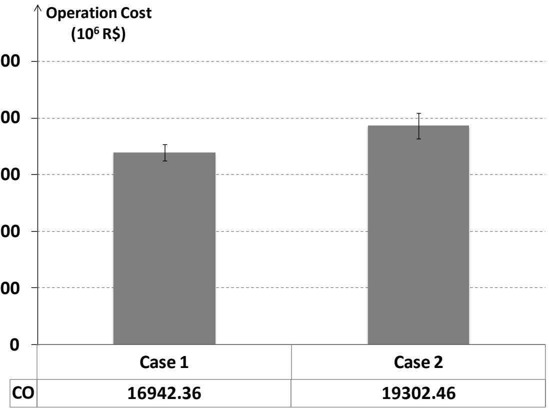

Figure 9 Expected value of total operation cost.

Table 1 and Table 2 show the probability of load curtailments (deficit) and expected energy not supplied, respectively. Case 2 presents more scenarios with deficit than Case 1. Table 3 presents the anual system marginal costs.

Table 1: Annual probability of deficit (%).

Case 1

	SE/CO	S	NE	N
2010	0.0	0.0	0.0	0.0
2011	3.8	5.8	4.1	3.6
2012	4.0	4.6	1.9	2.7
2013	2.2	2.3	0.4	1.6
2014	2.1	3.9	0.9	1.5

Case 2

	SE/CO	S	NE	N
2010	0.0	0.0	0.0	0.0
2011	4.7	6.3	4.1	4.3
2012	5.3	7.4	2.8	3.3
2013	3.2	4.8	0.5	1.5
2014	2.6	3.0	0.5	2.1

Table 2: Annual Expected Energy not Supplied (MW).

Case 1

	SE/CO	S	NE	N
2010	0.0	0.0	0.0	0.0
2011	29.9	8.1	4.3	2.5
2012	33.4	8.1	1.8	1.3
2013	22.0	6.1	0.0	1.3
2014	21.1	5.9	0.1	1.5

Case 2

	SE/CO	S	NE	N
2010	0.0	0.0	0.0	0.0
2011	35.2	8.1	5.6	3.5
2012	64.5	15.7	4.4	3.2
2013	40.0	11.0	0.0	1.6
2014	30.0	7.9	0.1	1.7

Table 3: System marginal costs (R$/MWh)

Case 1

	SE/CO	S	NE	N
2010	75.53	75.95	65.40	75.34
2011	93.34	93.59	87.44	87.86
2012	84.16	81.80	66.74	69.00
2013	76.56	74.72	55.49	64.86
2014	82.81	82.35	62.25	71.96

Case 2

	SE/CO	S	NE	N
2010	79.31	79.65	66.8	84.32
2011	101.24	95.48	94.76	96.57
2012	110.74	109.26	79.84	84.53
2013	95.22	95.32	61.91	72.97
2014	92.11	90.1	66.4	76.99

Figure 11 presents the expected hydro generation along the time horizon for both Cases 1 and 2. The hydro generation of SE/CO subsystem in Case 2 is obtained by the sum of hydro generation of SE/CO West, PR and IT subsystems and we can observe that it is less than the hydro generation of the correspondent subsystem in Case 1. In turn, subsystems South, Northeast and North have their hydro generation incresead.

Figure 12 presents the expected thermal generation along the time horizon for both Cases 1 and 2. The thermal generation of SE/CO subsystem in Case 2 is obtained by the sum of thermal generation of SE/CO West, PR and IT subsystems and we can observe that it is higher than the thermal generation of the correspondent subsystem in Case 1. Subsystems South, Northeast and North also have their thermal generation incresead.

Figures 13 and 14 illustrate, for Cases 1 and 2, the evolution along the planning period of expected storage energy and spillage of SE/CO subsystem respectively. It can be seen that the expected energy storages are very similar in both cases, but the spillage has increased when the hydroplant Itaipu was considered as a subsystem itself, allowing the explicit consideration of the interconnection of the Itaipu power plant with the subsystems South and Southeast/Central West. One can also credit part of these results to the hypothesis assumed in Case 1, that is, all the hydroplants in the same subsystem have the same hydrological characteristics. For example, when a hydroplant is passing by a drought period, it is assumed that all the hydroplants in the same subsystem is passing by the same drought period. As can be seen in table 4, that shows the spatial correlation between SE/CO West, Itaipu and Paraná subsystems, one of these subsystems can be passing a drought period without being followed by the others.

6 CONCLUSIONS

Coordinating the operation of the Brazilian generating system is a very complex task. Usually, the operation planning problem is divided in linked subproblems according to decision horizons. These horizons varies from long-term scheduling (1 to 5 years ahead) up to the short-term scheduling and dispatch. To keep the solution of the long-term operation planning problem computationally tractable, it is necessary to introduce simplifications to the original problem. One important approximation is the aggregation of system reservoirs into equivalent energy reservoirs models. However, the currently adopted methodology to construct the Equivalent Energy Model is only able to represent subsystems without hydraulic coupling. This paper showed an extension to the methodology to construct the Equivalent Energy Model that allows dealing with subsystems hydraulically coupled. A study case, with a configuration of the Brazilian generating system, involving Itaipu hydroplant was presented.

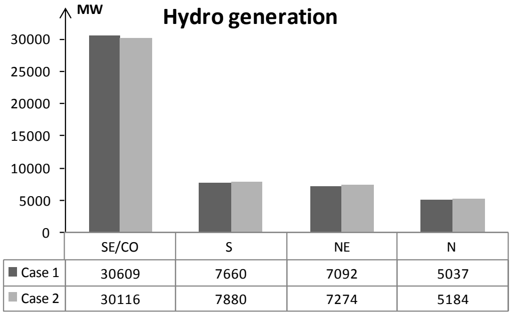

Figure 10 Total hydro generation (MW).

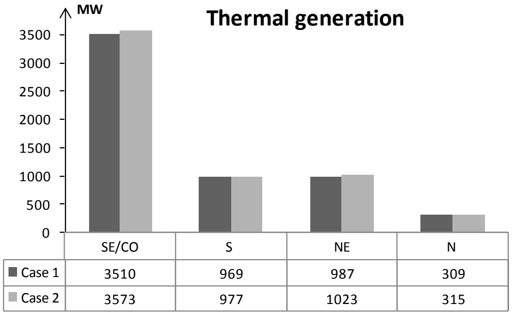

Figure 11 Total thermal generation (MW).

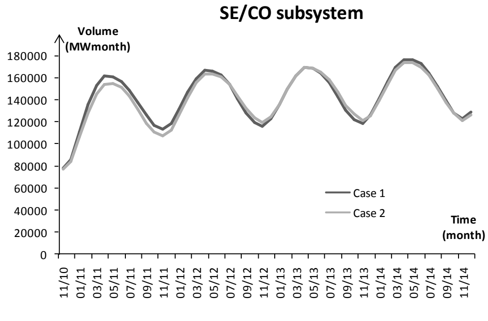

Figure 12 SE/CO expected storage energy.

Table 4: Cross-correlation of Case 2

	SE/CO	IT	PR
SE/CO	1.000	0.000	0.566
IT	0.000	1.000	0.515
PR	0.566	0.515	1.000

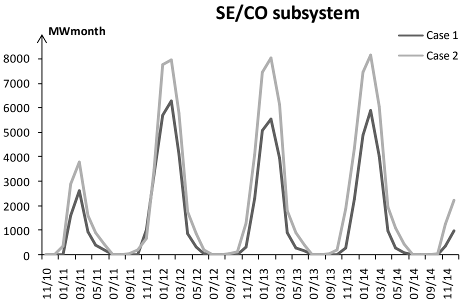

Figure 13 SE/CO expected spillage.

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