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Nuclear Fuel Replacement Schedule Impact on System Operation Costs

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Abstract: In the management of the nuclear combustible life-cycle, periodic shutdowns are necessary to replace and rearrange fuel elements in the core. During the weeks of maintenance other sources are used to supply the energy gap, typically at higher costs. However, in systems with large integration of renewable energy sources, where the energy availability and costs are seasonal, the shutdown schedule may play an important role in the system costs. Thus, this paper evaluates the impact of a nuclear power plant fuel replacement in the system operation, mainly in the supply of electricity and its costs. A part of the Brazilian southeast hydroelectric system was used to illustrate the impact of the shutdown scheduling and how the system planning can minimize its operation costs. The system operation costs were lower with the shutdown scheduled during the season with large availability of energy resources. However, in Brazilian hydro-dominated power system, this cost variation can be partially compensated by the modification the hydroelectric operation.

Resumo: No gerenciamento do ciclo de vida do combustível nuclear são necessárias paradas periódicas para substituição e rearranjo dos elementos combustíveis dentro do núcleo. Durante as semanas de manutenção, outras fontes são usadas para suprir a lacuna energética, tipicamente com custos mais altos. Todavia, em sistemas com grande disponibilidade de fontes renováveis de energia, onde a disponibilidade energética e os custos são sazonais, o planejamento das paradas pode ser significativo nos custos do sistema. Assim, este artigo avalia o impacto que a substituição do combustível de uma central nuclear causa na operação do sistema, principalmente na produção e custo da eletricidade. Uma parte do sistema hidroelétrico do sudeste brasileiro foi utilizado para ilustrar o impacto do planejamento das paradas e como o planejamento do sistema pode minimizar os custos de operação. Os custos de operação do sistema foram mais baixos durante os períodos de maior disponibilidade de recursos energéticos. Todavia, no sistema brasileiro, com grande participação de hidroeletricidade, o reflexo nos custos pode ser parcialmente compensado por modificações na operação dos reservatórios.

Keywords: Hydro-dominated Power System, Core Fuel Management, Nuclear Fuel Management, Optimization, Operation Planning.

Palavras-chaves: Sistema de Potência Dominado por Hidroeletricidade, Gerenciamento do Combustível do Núcleo, Gerenciamento do Combustível Nuclear, Otimização, Planejamento da Operação

1. INTRODUCTION

Nuclear energy is originated in the core of an atom which has proven to be a tremendous energy source. It is currently responsible for supplying a significant amount of energy worldwide. Nuclear power applications, for electricity conversion as an example, are typically based on fission reactions in large central power stations (Lamarsh and Baratta 2001).

In the most popular fission reactors commercially available, pressurized-water reactor (PWR) for instance, the nuclear fuel is contained inside a pressurized vessel and maintained critical while the heat from the reactions is extracted and used to power a turbine connected to an electrical generator. Therefore, one nuclear fuel load is planned to sustain its reactivity for several months, until an outage for fuel management (EIA 2011).

Due to the high cost of the fuel replacement and the complexity of the operation, core fuel management pursues the optimization of the core performance and longevity of the fuel. However, this is not the only cost involved in an outage operation. During the period in which the fuel is replaced and maintained, demand and consumption need to be supplied by other power plant installed in the system, with higher operation costs.

Therefore, this paper is intended to evaluate the impact of the maintenance outage of large nuclear power plants in the system. The methodology presented in this paper is aimed to contribute to the centralized system planning and operation, where planned outages of important power plants may require reschedule of the other plants in the system prior, during and after the outage.

A hydro-dominated system, such as the Brazilian system, in which cost of energy depends on the seasonal availability of the resources, has been used in the case study. A representative outage of low cost energy representing the nuclear source has been simulated and the system optimized to couple the operation to the outage condition. Multiple simulations were executed, representing outage in different periods along the year and the results were compiled and discussed in this paper with the objective to contribute to a holistic assessment in the nuclear core fuel management optimization.

2. OPERATION PROBLEM

In conventional thermal system with predominance of fossil fuel based power plants, cost of operation depends on fuel costs. Cost optimization in such system is a function of the marginal operation costs and the dispatch in merit order corresponds to be the more economical solution.

Hydroelectric power plants with reservoirs can storage energy from one period to the other, adding a temporal coupling to the problem. Thus, hydro-dominated system differs from traditional thermal systems because of the fact that costs of different sources and periods are coupled by the regulating capacity of the hydro reservoirs and influenced therefore by the inflow availability.

The operation problem consists of the optimization of total operational costs of an electrical power grid of multiple hydroelectric plants and its thermal energy complementation (including nuclear energy). Minimal costs is obtained with the scheduling of monthly energy dispatch of each hydroelectric power plant during the planning period, taking into consideration the forecasted behavior of rivers' inflows and energy consumption expectations. Additional complexity of this problem resides in the fact that whenever power plants are installed in the same river or in cascade, the availability of water in one plant depends on the operation of the plants upstream and operation decision of previous periods (Conceição et al. 2016).

3. MATHEMATICAL MODEL

The mid-long term hydrothermal operation planning model (Soares et al., 1980) have been adapted and the objective function can be written as:

$$\min_{\{x\}} C_O \tag{1}$$

where, C_O is the present value of the total operation cost, which is a function of the non-hydroelectric energy supplied at each time interval, t, along the total planning period, T. The cost minimization is, therefore, a function of the reservoirs control variable of operation (reservoirs volumes along the planning period, x).

$$C_O = \sum_{t=1}^{T} \frac{C_{oper}^{t}}{(1+J)^{t/12}} \tag{2}$$

A non decreasing function such as (3) has been selected (Soares et al. 1980, Lyra et al. 1984) to estimate the incremental cost of the energy produced by each source:

$$C_{oper}^{t} = (K_1 \cdot E_{thermal}^{t} + K_2 \cdot E_{nuclear}^{t})^2 \tag{3}$$

while the energy amount produced in each time step is calculated as follows:

$$E_{thermal}^{t} = D^t - GH^t - E_{nuclear}^{t} \tag{4}$$

where:

J	Interest rate
C_{oper}^{t}	Cost of energy from non hydroelectric sources in a time interval
$K_{1,2}$	Cost factor for each energy source
$E_{nuclear}^{t}$	Energy produced from the nuclear plant under evaluation in a time interval
$E_{thermal}^{t}$	Energy produced by thermal sources in a time interval
D^t	Consumption in a time interval

The costs of the hydropower generation, GH, is neglected once the model considers the use of existing plants which investment has been amortized and there are no combustible cost. Therefore, in order to keep the future costs of the hydro generation into consideration, the contour conditions are set to reestablish the reservoirs to the initial condition at the end of the planning period, T.

The hydropower generation is calculated by adding the power production of all N hydropower plants:

$$GH^t = \sum_{i=1}^{N} P_i^t\,(x_i^t, u_i^t, q_i^t) \tag{5}$$

where the power production, P_i^t, of each hydropower plant, i, at each time interval, t,is calculated as function of the reservoirs volumes, x_i^t, turbine inflow, q_i^t, and plant outflow, u_i^t:

$$P_i^t(x_i^t, u_i^t, q_i^t) = \left[h_{mon}^t(x_i^t) + h_{jus}^t(u_i^t)\ \right].q_i^t \tag{6}$$

$$h_{mon}^t(x_i^t) = a_0^i + a_1^i \cdot x_i^t + a_2^i \cdot (x_i^t)^2 + a_3^i \cdot (x_i^t)^3 + a_4^i \cdot (x_i^t)^4 \tag{7}$$

$$h_{jus}^t(u_i^t) = b_0^i + b_1^i \cdot u_i^t + b_2^i \cdot (u_i^t)^2 + b_3^i \cdot (u_i^t)^3 + b_4^i \cdot (u_i^t)^4 \tag{8}$$

subject to the energy balance of (4) and:

$$\Delta x_i(t) = In_i^t - u_i^t + \sum_{j \in \Omega_i} u_j^t \tag{9}$$

$$In_i^t = yn_i^t - \sum_{j \in \Omega_i} yn_j^t \tag{10}$$

$$u_i^t = q_i^t + z_i^t \tag{11}$$

$$x_i^0 = x_i^T \tag{15}$$

$$x_{min,i} \leq x_i^t \leq x_{max,i} \tag{16}$$

$$q_{min,i} \leq q_i^t \leq q_{max,i} \tag{17}$$

$$0 \leq E_{thermal}^t \leq E_{thermal}^{max} \tag{18}$$

$$GH^t,\ u_i^t, z_i^t \geq 0 \tag{19}$$

where:

x_i^t	Volume of reservoir in a time interval
u_i^t, u_j^t	Controlled flow through dam in a time interval
q_i^t	Controlled flow through turbine in a time interval
z_i^t	Spillage flow in a time interval
h_{mon}^t	Net height upstream in a time interval
h_{jus}^t	Net height downstream in a time interval
a_0^i ... a_4^i	Parameters of the volume function
b_0^i ... b_4^i	Parameters of the stream function
In_i^t	Incremental flow
yn_i^t, yn_j^t	Natural flow in a time interval
$x_{min,i}$, $x_{max,i}$	Minimal and maximal volume of a reservoir
$q_{min,i}$, $q_{max,i}$	Minimal and maximal flow through a turbine

With the structure supported by this mathematical model a case study has been proposed with the aim to evaluate the operation cost sensitivity of a nuclear power plant shutdown (core fuel maintenance) in different periods along the year.

4. CASE STUDY

Three power plants with reservoirs from the Brazilian power system were used in the simulation: Emborcação, Itumbiara and São Simão. The power plants were erected along the Parnaiba River in a way that the operation of one power plant impact in all other plants located downstream, see Fig. 1.

The run-of-the-river plant, Cachoeira Dourada, in the same river was not considered in the case study once the power produced there is not controlled locally.

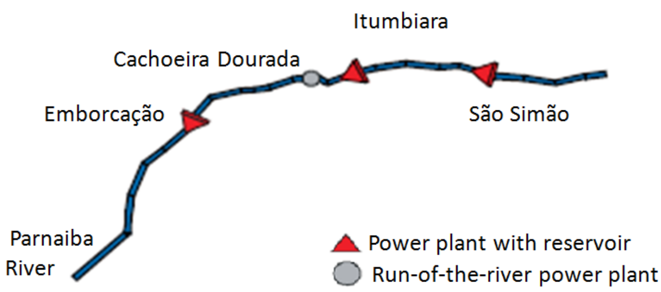

Fig. 1. Spatial location of the power plants used in the case study along the Parnaiba River.

Tables I and II contains the technical data of the power plants and the deterministic factors used for the simulations of this case study respectively (Asano Jr., Casella and Leite 2019).

TABLE I
POWER PLANTS TECHNICAL PARAMETERS

	Emborcação $i = 1$	Itumbiara $i = 2$	São Simão $i = 3$
Installed Power [MW]	1192	2080	1680
Max. Volume [hm^3]	17190	17027	12540
Min. Volume [hm^3]	4669	4573	7000
Max. turbine flow [hm^3/month]	2754.1	8467.4	11826.0
Min. turbine flow [hm^3/month]	199.7	667.5	1072.2
a_0^i	0.1550	0.12499	0.1242
a_1^i	0.4819E-4	0.2446E-4	0.2959E-4
a_2^i	-0.3996E-8	-0.1885E-8	-0.3037E-8
a_3^i	0.1937E-12	0.8727E-13	0.1818E-12
a_4^i	-0.3736E-17	-0.1628E-17	-0.4265E-17
b_0^i	0.0000	0.0000	0.0000
b_1^i	-0.5053E-5	-0.2040E-5	-0.2526E-6
b_2^i	0.5285E-9	0.3978E-10	-0.5638E-10
b_3^i	-0.4290E-13	-0.5874E-15	0.12545E-14
b_4^i	0.1229E-17	0.0000	-0.84019E-20

TABLE II
SEASONAL PARAMETERS

	D^t [MWmonth]	yn_i^t [hm^3/month] Emborcação $i = 1$	Itumbiara $i = 2$	São Simão $i = 3$
Jan.	4430.4	2103	6244	9489
Feb.	4545.6	2171	6697	10130
Mar.	4651.2	2025	6327	9808
Apr.	4646.4	1501	4750	7440
May	4756.8	964	3081	4828
Jun.	4838.4	736	2373	3720
Jul.	4944.0	583	1871	2946
Aug.	4977.6	452	1468	2321
Sep.	4963.2	384	1260	1989
Oct.	5025.6	493	1627	2546
Nov.	4920.0	850	2650	4042
Dec.	4900.8	1532	4473	6844

A nuclear power plant of 100MW and capacity factor of 92% was used. It represents about 2% of the energy consumption which is equivalent to the participation of nuclear power in current Brazilian electricity mix of primary energy sources (Brasil 2019). The cost factor K_2 of nuclear energy was adjusted to a fraction of K_1 in order to reproduce the preference of nuclear energy dispatch.

5. RESULTS AND DISCUSSIONS

In order to evaluate the impact of the energy shortage in the operation costs, twelve different simulations were executed, each one considering the outage of the nuclear power plant in one month of the year, keeping all other parameters constant, from one simulation to the other. In addition to that, in order to establish a benchmark, the hydrothermal system operation has also been optimized without any outage. Starting with this benchmark operation it is possible to evaluate different scenarios where the energy gap due to the nuclear plant outage is filled only by other thermal (fossil fuel) plants as well in the case where the hydroelectric planning is modified.

Due to the nonlinear nature of the problem, an evolutionary meta-heuristic (Asano Jr 2018), was applied with the mathematical model of Session 3. This optimization technique was developed based on species evolution immersed on social environment and is named Evolutionary Socio-Bio Inspired Technique (ESBIT). In this algorithm individuals (each individual correspond to a complete solution or the values of state variables) are grouped into multigenerational societies or colonies which interact within the colony as well with other colonies along the evolution process (Leite, Gramulia Jr. and Asano Jr. 2018). Besides the multigenerational characteristic, which allows a broader range of reproduction strategies, with ESBIT, the complexity is also adjusted during the evolution process. Thus, based on this architecture, this new technique has been used for this problem of difficult solution, where the search space need to be explored efficiently.

Fig. 2 presents the operation marginal cost variation depending on the planned calendar month of outage. The marginal cost index represents the ratio between the relative cost increase by the relative non nuclear energy increase in both cases, with and without hydroelectric rescheduling.

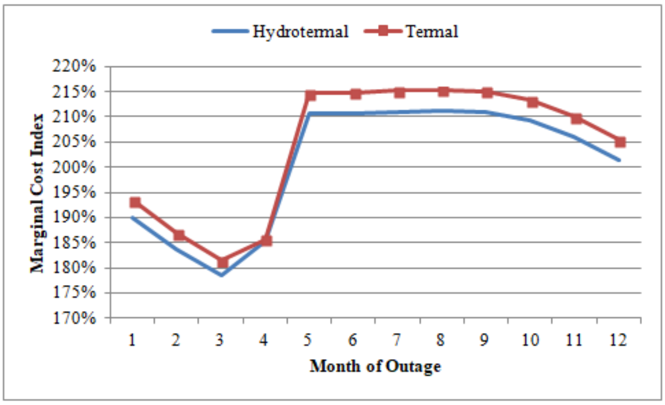

Fig. 2: Operation costs in different outage month.

These results show that lower costs of operation are reached if the outage is scheduled during the early months of the year, corresponding to the rainy season. In this case, overall marginal costs are lower due to the abundance of water to supply the hydroelectric plants.

It is also remarkable, from the comparison between the two lines, that the consideration of the outage in the operation planning reduces its cost impact.

Fig. 3 shows the hydroelectric and thermal energy delivered for the outage planned to the month 3 (March) which represents the less costly scenario. It can be compared to the case where the outage is planned to the month 8 (August) in the middle of the dry season (Fig. 4).

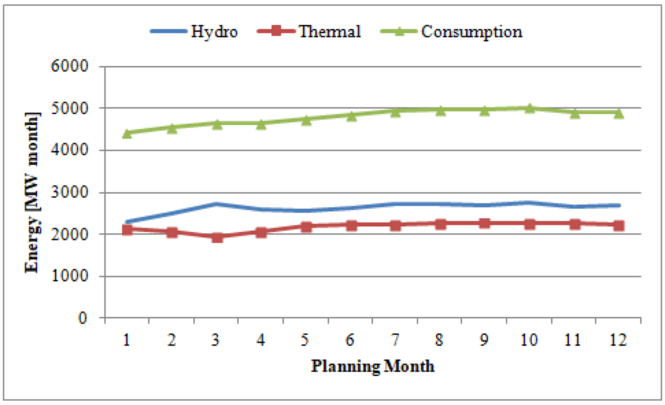

Fig. 3: Energy profile considering the outage in March.

In this case (outage in August), a different strategy is taken up to August, in order to minimize the effects of the outage in that month. Thus the cost of this modified operatio is distributed along the planning horizon, minimizing the outage impact in the global costs as observed in Fig. 2.

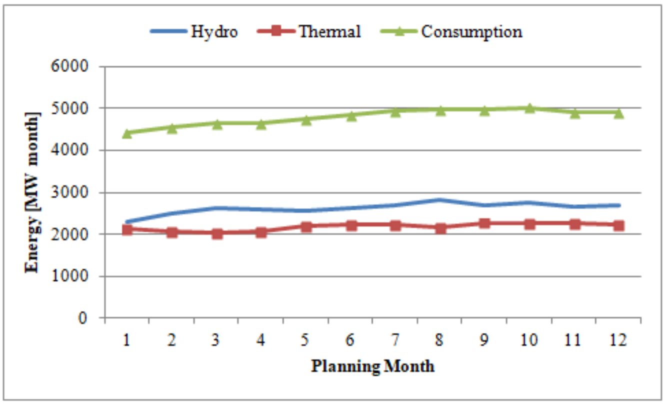

Fig. 4: Energy profile considering the outage in August.

Finally, Fig. 5 and 6 compares the variation (as a percentage of the operational volume) in the reservoirs operation (from the benchmark) required in both conditions (March and August outages). The chart shows only Emborcação and Itumbiara once they regulate the flow to São Simão which optimally operates as a run-off-river in all scenarios.

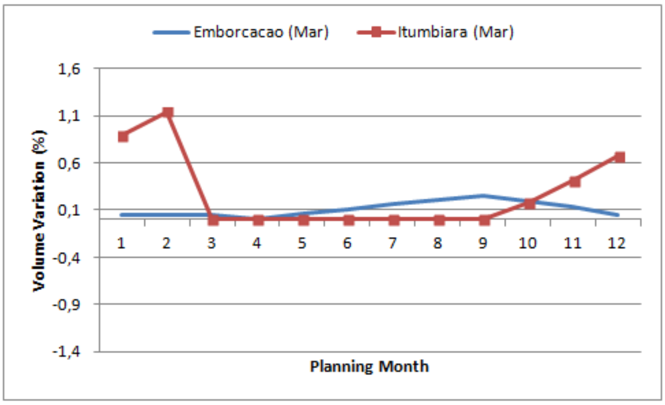

Fig. 5 Variation in reservoirs operation trajectory (March outage).

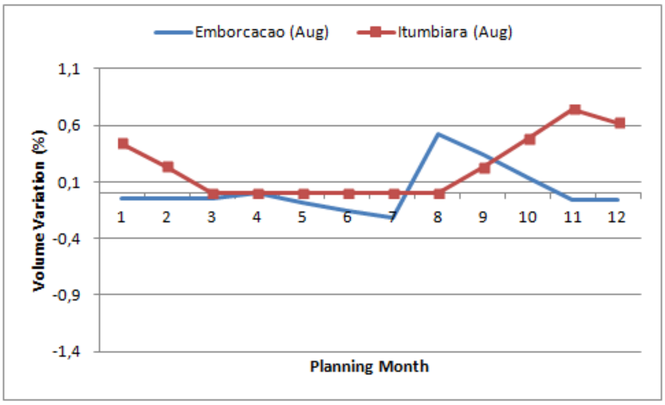

Fig. 6 Variation in reservoirs operation trajectory (August outage).

While the variation of Fig. 5 is intuitive, with more water been accumulated during the wet season (starting in October) to increase the discharge and produce extra power in March, the additional power extracted in the month of August illustrate in Fig. 6 is obtained by a slightly higher reservoir level (h^{t}_{mon}) once the water inflow availability is much more limited in the middle of the dry season.

6. CONCLUSION

This paper has evaluated the impact of a maintenance shutdown of a nuclear power plant in the system operation planning along the year.

The system operation costs were lower with the shutdown scheduled during the season with large availability of energy resources. However, in Brazilian hydro-dominated power system, this cost variation can be partially compensated by the modification the hydroelectric operation. It is important to highlight that an adequate planning of the diversified generation mix can benefit the society with energy security and moderate costs.

System operation cost is one of the factors that need to be evaluated in the decision of scheduling the maintenance of a large power plant. Availability of power capacity to meet demand and the efficiency or exhaustion of the reactor core are other main drivers that must also be considered, but were not in the scope of this paper.

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