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Performance evaluation and energy production optimization in the real-time operation of hydropower plants

M.M. Cordova [a,*], E.C. Finardi [a], F.A.C. Ribas [b], V.L. de Matos [a], M.R. Scuzziato [a]

[a] LabPlan/UFSC, Electrical Systems Planning Research Laboratory, Federal University of Santa Catarina, Campus Universitário, CP 476, CEP 88040-900 Florianópolis, Brazil

[b] Tractebel Energia – GDF Suez, CEP 88025-255 Florianópolis, Brazil

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ABSTRACT

This paper describes a system for the performance evaluation and energy optimization of the real-time operation at Itá Hydropower Plant, which is located in southern Brazil. Using data collected from sensors and meters, several variables of the units are precisely calculated, such as turbined outflows, heads, losses and efficiencies. The unit turbined outflow, which is the most challenging and important parameter for real-time operation, is calculated using an ultrasonic flow meter and a Hill diagram. Additionally, the system performs a real-time optimization in which the dispatch aims to use the water efficiently. In predominant hydropower systems, as in Brazil, this computational tool is very useful for the efficient use of hydro resources, for which every tenth of a percentage increase in the energy conversion efficiency is welcome. The benefits detailed in this paper can also be achieved in other plants, particularly if there are a large number of units with distinct operating characteristics.

1. Introduction

Hydropower plants provide the major portion of electricity production in the Brazilian interconnected system (BIS). Consequently, due to the complexities that can be seen in Refs. [1,2], the operation planning problem must be performed for different time horizons, each with its own mathematical characteristics. In Brazil, an independent system operator (ISO) uses optimization models to solve the medium and long-term [3,4] operation planning problems. However, for the issue of the daily operation scheduling (DOS), which is a day-ahead operation planning problem, the ISO does not possess an optimization tool to efficiently use the generation resources, considering the nonlinearities and non-convexities inherent to the DOS problem [5,6]. In Brazil today, the DOS problem is performed based on generation policies supplied by the medium-term model and aims to provide, for each hour of the next day, an energy target for each hydro plant of the BIS. To maintain the medium-term (and, therefore, the long-term) system optimization, it is important that hydro generation companies avoid violating the generation target provided by the ISO and, additionally, perform the dispatch appropriately. In this paper, considering that the BIS is predominantly hydroelectric, the goal is to use water efficiently, i.e., by using the minimum amount of water (plant turbined outflow) that meets the energy target provided by the ISO. The key aspect (and the most difficult) is to precisely determine the turbined outflow of each generating unit, which is intrinsically related to the modeling of the hydropower function and the measurement methods of various parameters in the real-time operation of the hydro plant.

The quest for efficient hydroelectric operation has been addressed in several papers. For example, Ponrajah and Galiana [7] present a methodology for the economic dispatch and the optimal selection of generation units in the real-time operation. Arce et al. [8] propose an optimization model for the Itaipu hydro plant. Bortoni et al. [9] present a strategy for determining the optimal distribution of the load between the generating units. Breton et al. [10] address the optimization problem of water resources through the dynamic programming methodology, also considering the network constraints. Siu et al. [11] present a dynamic unit commitment and loading model that considers different generating units and complex hydraulic configurations. Finardi and Silva [12] propose a nonlinear integer-mixed problem model for solving the unit commitment problem of a single hydroelectric plant.

This paper describes an innovative system for the real-time performance evaluation and optimization of energy production in the real-time operation of a hydro plant. To the best of the knowledge of the authors, no such system exists. Based on data collected in real-time by level and pressure sensors, as well as the turbined outflow ultrasonic flow meter, the system performs several

* Corresponding author. Tel.: +55 48 3721 9731; fax: +55 48 3721 7538.
E-mail addresses: cordova.m@posgrad.ufsc.br, cordova.mm@gmail.com (M.M. Cordova).

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evaluations of the real-time operation and solves an optimization model to provide the generation output with the lowest water-specific consumption for an energy target supplied by the ISO. The system possesses two specific modules: (i) real-time performance evaluation; and (ii) real-time optimization. In (i), the objective is to determine the operating condition of the generating units and the plant, in which powers, losses, and efficiencies are calculated, considering the entire process of energy conversion. Thus, the plant operator obtains detailed information about each parameter: hydraulic load losses, turbine and generator efficiencies, net head, etc. On the other hand, in (ii), the system performs the generating units dispatch: the optimal distribution of generation between all units, considering the energy target provided by the ISO, is obtained with a minimum water-specific consumption. To supply an accurate dispatch, the system considers a detailed modeling of the physical characteristics of the reservoir and the generating units.

This paper is organized as follows: Section 2 presents the nomenclature; Section 3 presents the hydropower function modeling; in Section 4, we use this modeling in the real-time module and present, via algorithms, how the model is applied in the system; Section 5 presents the optimization module in which the hydropower function is the basis of an optimization problem; Section 7 presents some numerical results that consider real operating conditions; and finally, the conclusions are presented in Section 8.

2. Nomenclature

The notation used throughout the paper is presented below.

η_i	turbine hydraulic efficiency of unit i
θ	constant with value 0 if $0 \le T \le 20$ or 20 if $20 < T \le 50$ (°C)
Θ	plant specific consumption [$m^3/(s\,MW)$]
σ	water density (kg/m^3)
ϕ	latitude of the hydro plant (°)
bl_i	thrust bearing losses of unit i (MW)
Bt_i	turbine hydraulic thrust of unit i (N)
csc_i	elevation of the spiral casing inlet of unit i (m)
Dg_i	portion of thrust bearing losses referent to the generator of unit i
Dt_i	portion of thrust bearing losses referent to the turbine of unit i
fbl	reservoir forebay level (m)
trl	reservoir tailrace level (m)
g	gravity acceleration (m/s^2)
ggl_i	generator global losses of unit i (MW)
gp_i	output electrical power of unit i (MW)
hll^{atm}	hydraulic losses due to the difference of atmospheric pressure between fbl and trl (m)
$k0$	theoretical coefficient associated with the load losses in the canal intake (s^2/m^5)
kx_i	theoretical coefficient of hydraulic load losses of unit i associated with x, in which $x = 1$ if it refers to trash rack losses, $x = 2$ if it refers to the penstock losses or $x = 3$ if it refers to the draft tube losses (s^2/m^5)
k_i^{ag}	aggregated coefficient of hydraulic load losses of unit i (s^2/m^5)
lcr_i	elevation of the turbine rotor of unit i (m)
N	number of generating units in the plant
nh_i	net head of unit i (m)
P	plant generation set point determined by the ISO (MW)
$pg_{ij}^{min(max)}$	minimum (maximum) electrical output power of unit i (MW)
psc_i	pressure at the spiral casing inlet of unit i (Bar)
prt_i	ambient pressure in the turbine's rotor of unit i (Pa)
q_i	turbined outflow of unit i (m^3/s)
$q_{ij}^{min(max)}(\cdot)$	minimum (maximum) turbined outflow of unit i, as a function of its net head (m^3/s)
Q	plant turbined outflow (m^3/s)
R_{zw}	element (z, w) of the matrix of coefficients that relates σ with T (kg/m^3)
s	spillage (m^3/s)
Ssc_i	area of the spiral casing inlet section of unit i (m^2)
tml_i	turbine mechanical losses of unit i (MW)
T	water temperature in the reservoir (°C)
u_i	binary variable that indicates whether the unit i is operating ($u_i = 1$) or not ($u_i = 0$)
Wg_i	generator weight of unit i (N)
Wt_i	turbine weight of unit i (N)

3. Hydropower function

The electric power output of a hydro generating unit i can be described by means of Eq. (1), which is known as the hydropower function:

$$gp_i = 10^{-6} \cdot g \cdot \sigma \cdot q_i \cdot nh_i \cdot \eta_i - tml_i - ggl_i, \quad (1)$$

where 10^{-6} is a constant used to convert W into MW. According to Ref. [13], g depends on the plant location, i.e., its latitude and elevation relative to the sea level:

$$g = 9.7803 \cdot [1 + 0.0053 \cdot \sin^2(\phi)] - 3 \cdot 10^{-6} \cdot lcr_i. \quad (2)$$

The water density, σ, is a function of the water temperature, T, and the elevation relative to the sea level. This parameter is calculated, according to Ref. [13], as follows:

$$\sigma = \frac{100}{\sum_{z=0}^{3}\sum_{w=0}^{3} R_{zw} \cdot (T-\theta)^{w} \cdot \left[10^{-5} \cdot [101,325 \cdot (1 - 2.2558 \cdot 10^{-5} \cdot lcr_i) + 2 \cdot 10^{7}]\right]^{z-1}}. \quad (3)$$

In Eq. (3), R_{zw} and θ are constants.

For Eq. (1), the net head of unit i is defined as:

$$nh_i = fbl - trl - k0 \cdot \left(\frac{q_i}{Q}\right) \cdot Q^2 - k_i^{ag} \cdot q_i^2 - hll^{atm}, \quad (4)$$

where the hydraulic load loss due to the difference in the atmospheric pressure between the forebay and the tailrace levels, hll^{atm}, is obtained as follows [13]:

$$hll^{atm} = \frac{101,325}{\sigma \cdot g}\left[(1 - 2.2558 \cdot 10^{-5} trl)^{5.255} - (1 - 2.2558 \cdot 10^{-5} fbl)^{5.255}\right]. \quad (5)$$

In Eq. (4), fbl, obtained from a level sensor, is considered a constant in the system because in real-time operation, fbl has a small variation through successive simulations. The second term in Eqs. (4) and (5), trl, is also obtained from a level sensor in real-time operation. On the other hand, in the optimization module, the trl is modeled by means of a polynomial function, as shown in the following. The third term in Eq. (4), $k0(q_i/Q)Q^2$ is the portion of the hydraulic losses associated with the canal intake of the generating unit i, where Q is the plant turbined outflow. Finally, the fourth term in Eq. (4) includes the effect of hydraulic load losses in the remaining portion of the hydraulic circuit, i.e., the trash rack, the penstock and the turbine draft tube. The accurate inclusion of these losses is a challenging task, and the strategies adopted in the system are shown later.

For real-time operation, the turbine hydraulic efficiency of unit i, η_i, may be determined by means of two methods, which are also detailed later. Finally, related to the hydropower function (1), the turbine mechanical losses tml_i and the generator global losses ggl_i must be defined. The tml_i are obtained by field tests and may be divided into three parts: losses due to mechanical friction in the guide bearings, losses due to shaft seals, and losses due to the thrust bearing. The first one is modeled as function of gp_i. The portion due to shaft seals is assumed constant. The losses due to the thrust bearing, bl_i, are obtained in field tests, in which a curve relating the losses with gp_i is obtained. The tml_i are divided into two