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Optimal scheduling of a hydro basin in a pool-based electricity market with consideration of transmission constraints

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ABSTRACT

The effect of flexible hydropower management on prices is a topic widely studied in research and economic analysis. However, the influence of transmission constraints and zonal prices on optimal hydro dispatching has not been highly considered in the literature. In the present study, an iterative algorithm for calculating the optimal bids of hydro plants in a basin is proposed, considering the fundamental influence of these plants in regions when transmission lines are congested and can affect zonal prices. The results show the efficiency of the algorithm and modifications in positioning of hydro plants in the market.

1. Introduction

The optimal planning of hydro producers is crucial in many power systems due to the flexible characteristics of these plants. Hydro plants produce electricity at almost null variable cost and have good controllability abilities, allowing for increased renewable source participation in the generation mix. However, the optimal planning of these plants presents significant challenges due to the technical interrelationships between plants in the basin and the influence of these producers on the electricity market.

Many studies have been performed to calculate the optimal operation of a hydro basin. In medium and short-term planning, Habibollahzadeh and Bubenko [1] applied different mathematical alternatives (Heuristic, Benders and Lagrange methods) for obtaining optimal hydroelectric generation scheduling in the Swiss system. Zhao and Davison [2] analyzed the inclusion of storage facilities in a hydro system, demonstrating the sensitivity of parameters of the hydroelectric facility, expected prices and water inflows. Castronuovo and Lopez [3] described economic profit resulting from the coordination of wind and hydro energies. Pousinho et al. [4] proposed a mixed-integer quadratic programming approach for a short-term hydro scheduling problem that considered discontinuous operating regions and discharge ramping constraints. Simopoulos et al. [5] proposed a decoupling method, dividing the hydrothermal problem into hydro and thermal subproblems, which were solved independently; a Greek system was analyzed in the study. Diniz and Maceira [6] used a four-dimensional piecewise linear model for the generation of a hydro plant as a function of storage, turbined and spilled outflows. Shawwash et al. [7] discussed the optimization model used in the British Columbian hydro system for hydrothermal coordination. Perez-Díaz and Wilhelmi [8] assessed the economic impact of environmental constraints in the operation of a short-term hydropower plant. A revenue-driven daily optimization model based on mixed-integer linear programming was applied to calculate the optimal operation of a hydro power plant (HPP) in the northwest area of Spain. Perez-Díaz et al. [9] propose adding a pumping capability to improve the economic feasibility of a HPP project, always fulfilling the environmental constraints imposed on the operation of the hydropower plant. Martins et al. [10] propose a novel nonlinear model for medium-term hydrothermal scheduling with transmission constraints. In this work, the IEEE Reliability Test System [11] and the Brazilian power system are used to test the proposed method. In [12], Fujisawa et al. use the Ward equivalent and DC power flow to calculate the optimal medium-term hydro-thermal scheduling of a basin.

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Obtaining an adequate representation of hydro plants integrated in a basin for using in market studies is also a present challenge. Conejo et al. [13] proposed a method for calculating the self-scheduling of a hydro generating company in a pool-based electricity market. The market prices were assumed as known and the authors used a mixed-integer linear programming model for representing the nonlinear relationship between the power produced, water discharged, and head of the reservoir plants. Borghetti et al. [14] extended the analysis for a pumping storage hydro plant, also considering a fixed price for all the hours. Simoglou et al. [15] calculated the optimal self-scheduling of a power company with a dominant role in both the production and retail sectors of an electricity market. Mixed integer linear programming formulation was used for the representation of the plant. Angarita and Usaola [16] analyzed the problem of the combined offers of hydro and wind units to obtain the maximum profit in a joint operation. Market prices were previously known for the analysis, and the hydro plant was represented by using power and energy restrictions. Catalão et al. [17] considered a detailed nonlinear representation of a cascaded hydro system, calculating the optimal operation for specified prices in the market. Kardakos et al. [18] calculate the optimal offering strategy problem of a strategic producer with sufficient number of both thermal and hydro generating units to take advantage of its strategic position. A bi-level formulation is used in the solution of this problem.

In most previous studies, the representation of the market is simplified, aiming more to improve the hydro plant modeling. However, because the schedule of hydro plants can affect market prices, a better model that includes other market participants' behavior is required. Many representations of day-ahead markets have been used in literature. In particular, the electricity market is characterized by a highly concentrated ownership structure together with an inelastic demand and limited transmission capacities, which makes it particularly sensitive to the abuse of market power. Hoobs et al. [19] have identified four primary distinct approaches for addressing questions concerning market power in electricity markets, namely: ex-post analyses of existing markets, market concentration analyses, laboratory experiments and modeling. Generally, it is acknowledged that these approaches cannot fully take into account the special characteristics of electricity markets such as structural, behavioral and market design factors that are related to market power. Therefore, oligopoly models have been typically used for market power analysis in electricity markets, as the special characteristics of electricity markets can explicitly be incorporated into oligopoly models. Ventosa et al. [20] have identified three main trends of electricity market modeling, namely optimization models, equilibrium models and simulation models. Equilibrium models have been extensively used for power market analysis as they are robust and flexible and have the potential to apply to very large systems. A detailed survey on equilibrium power market models can be found in [21,22]. Equilibrium models differ in many ways, including market mechanisms simulated, modeling of the electric network and the type of strategic interaction or game assumed. The results of equilibrium market models highly depend on the type of interaction assumed among rival firms and other players. The types of strategic interactions assumed in literature on power market modeling include the Bertrand and Cournot strategies [23,24], collusion, Stackelberg, General Conjectural Variations (CVs), supply function equilibria (SFE) [25,26] and conjectured supply function (CSF) [27,28]. Ruiz and Conejo [29] propose a method to determine the best bid strategy for a power producer in a pool-based electricity market with endogenous formation of prices. Uncertainties and congestions are considered in the analysis.

This paper presents an iterative algorithm for calculating the optimal energy bids of a set of HPPs in the day-ahead market, taking into account the possibility that congestions and market splitting take place. This study presents a new two-step nested algorithm that, starting from an optimization of hydro plants in a basin and based on a given electricity price, finds the optimal bid to maximize hydro generator profit. This bid is submitted to the electricity market simulation and the new market prices are found, taking into account a suitable market model including transmission constraints. The procedure is iterated until an equilibrium point is found. The nested algorithm is based on the integration of an adequate representation of the market (based on [30]) and an adequate optimization of the considered hydro plant operation in a basin (based on [31]). The algorithm was applied to a real basin in the Chiese river (Northern Italy) and evaluated using real Italian market data of October 2012. For some hours of the day, transmission congestions in the grid system restrict the flows between the Northern and other regions. Therefore, the price in the Northern region is different from that of the other Italian regions during these hours. When the market splits in regional markets, hydro plants are in the condition of influencing the zonal market price in the Northern region. The results show the efficiency of the algorithm, reaching convergence in only five iterations in most cases.

2. Hydro generation

Hydro plants in a basin cannot be considered as independent producers in the market, because the availability of energy in one of the plants depends on the ability to store water, proper water inflows and the water delivered by upper hydro plants into the same basin. Moreover, the water delivered by upper hydro plants is available for production in the lower hydro plant after a determined travel time between the plants.

Therefore, the hydro plants in a basin cannot be adequately aggregated into one equivalent, large hydro plant. Water flowing between hydro plants cannot be used for production until it reaches the next reservoir, changing the energy availability hourly. Additionally, water in the upper power reservoirs has an inner value higher than in lower ones, because it can be used to produce energy in more hydro plants. It should also be noted that the relationship between produced energy and water is a nonlinear mathematical expression, depending on the height and shape of the reservoir.

In the present study, the best operation of hydro plants in a basin is obtained by the solution of an optimization problem [31], where restrictions to the operation are modeled as mathematical constraints and prices are considered fixed values. The formulation of the problem is described by Eqs. (1)–(15).

$$\text{Max.} \quad \sum_{i=1}^{nr+nwr} \sum_{t=1}^{T} \left(C_t \cdot P_{i,t} \right) \tag{1}$$

$$\text{s.t} \quad V_{i,t} = V_{i,t-1} + V_{i,t}^{AF} + V_{i-1,t} - V_{i,t}^{T} - V_{i,t}^{C} - V_{i,t}^{D} \quad i = 1, \ldots, nr \tag{2}$$

$$V_{i,t}^{AF} + V_{i-1,t} - V_{i,t}^{T} - V_{i,t}^{C} - V_{i,t}^{D} = 0 \quad i = 1, \ldots, nwr \tag{3}$$

$$V_{i-1,t} = \sum_{\alpha i} \left(V_{i-1,t-t_v}^{T} + V_{i-1,t-t_v}^{D} \right) \quad i = 1, \ldots, (nr + nwr) \tag{4}$$

$$V_{i,1} = V_{i,1}^{SP} \quad i = 1, \ldots, nr \tag{5}$$

$$V_{i,T} = V_{i,T}^{SP} \quad i = 1, \ldots, nr \tag{6}$$

$$P_{i,t} - \eta_i \cdot V_{i,t}^{T} \cdot g \cdot h_{i,t} = 0 \quad i = 1, \ldots, (nr + nwr) \tag{7}$$

$$h_{i,t} = k_{0,i} + k_{1,i} \cdot (V_{i,t}) + k_{2,i} \cdot (V_{i,t})^2 + k_{3,i} \cdot (V_{i,t})^3 + k_{4,i} \cdot (V_{i,t}^{T}) + k_{5,i} \cdot (V_{i,t}^{T})^2 \quad i = 1, \ldots, (nr + nwr) \tag{8}$$