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Short term hydrothermal scheduling with bilateral transactions via bundle method

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Abstract

This paper presents a dual approach to solve the short term hydrothermal scheduling (STHS) problem for systems under pool–bilateral markets. First of all, the bilateral transactions and the spot market trades are discriminated in the STHS model. Subsequently, the resulting problem is decomposed into one hydro and a set of electrical and thermal subproblems. The subproblems are solved analytically or by a primal-dual interior point method, whereas the dual problem is solved via bundle method. The commitment status of the generating units is considered known and an augmented Lagrangian is used to define the dual problem. Performance indices are used to analyze the potential of chosen combinations of pool and bilateral trades. The performance of the bundle method is compared to that of a conjugate gradient method. Results are presented for two test systems.

Keywords: Short term hydrothermal scheduling; Bilateral transactions; Augmented Lagrangian; Bundle method

1. Introduction

The short term hydrothermal scheduling problem has been subject of considerable research in the last 20 years. The first computational methods were proposed to solve the problem defined for a single load bus. Subsequently, the transmission network was represented through its linear model [1–7]. The non-linear network model has been recently introduced into the problem [8]. In addition, the commitment status of the generating units has been treated as a decision variable [9–11].

A variety of optimization methods has been applied to the STHS problem, many of them associated with decomposition techniques, which includes Lagrangian relaxation [2,8–11]. Most of the approaches use a network flow programming algorithm to solve the hydro problem. The solution of the electric problem considering network constraints has been obtained using linear programming [4,5], network flow programming [6,7] or interior point methods [8]. In case integer variables were considered, the network constraints have also been represented through an augmented Lagrangian [11]. The master problem, on the other hand, has been solved using linear or quadratic programming or, in case the Lagrangian relaxation is adopted, via gradient based methods [1,2,8]. If integer variables are considered, subgradient based methods [11,12] or bundle methods [9,10] have been applied.

The restructuring process of the electric energy sector has brought about a redefinition of the obligations, roles and practices of the power companies. Under bilateral or pool–bilateral energy markets, the dispatch must guarantee the minimum deviations of the transactions from the accorded values. Some methodologies have been proposed to perform this task [13–15]. A number of works analyzed the effects of deregulation on hydro-thermal systems. In [16] a methodology is proposed for pricing power transactions in such systems based on the value of the stored water. Studies have also been made of the

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problem of purchasing and selling power considering constraints imposed by the commitment and dispatching of the units [12]. The impact of power transactions on the system operation and on transmission losses has been analyzed as well [17].

The present work is a continuation of the study presented in [17]. It proposes a STHS model in which the bilateral transactions and the spot market trades are discriminated. A decomposition approach based on Lagrangian relaxation is used to solve this problem. The relaxation decomposes the STHS problem into a master (dual) problem and the thermal generation, the transmission and the hydro scheduling subproblems. The master problem is solved via bundle method, the hydro and the transmission subproblems are solved via primal dual interior point method and the thermal generation subproblem is solved analytically. To improve the rate of convergence of the bundle method, an augmented Lagrangian is used. The commitment status of the generating units is considered known. Performance indices are used to analyze the pool and bilateral trades. To better analyze the performance of the bundle method, this approach is compared to a conjugate gradient method. Results are presented for the Ward–Hale system and an equivalent of the Brazilian system [18].

The paper is organized as follows. First of all, the STHS problem and the performance indices are derived. Subsequently, the relaxation procedure is explained and the master problem and subproblems are described. Next, the algorithm based on the bundle method is explained and the conjugate gradiente method is briefly described. Some test results are then analyzed and, finally, some conclusions are put forward.

2. The pool–bilateral short term hydrothermal scheduling problem

2.1. Network modeling

Under pool–bilateral markets, in every period of the planning horizon, it is possible to define a virtual network that is composed of all bilateral transactions accorded by the agents [14]. Supposing that the transactions are accorded directly by generation and load agents, to this network is associated a transaction matrix, $\mathbf{T}$, whose elements represent the value in pu or MW of the transactions. For a system with n buses we have

$$\mathbf{T} = \begin{bmatrix} t_{11} & \dots & t_{1n} \\ & \ddots & \\ t_{n1} & \dots & t_{nn} \end{bmatrix}, \tag{1}$$

where t_{ik} is the transaction between a generator at bus i and a load at bus k. Usually, $t_{ik} \neq t_{ki}$. In addition, $\mathbf{T}$ is defined such that the total active thermal and hydro generation at a bus i associated with bilateral contracts are $P^{\mathrm{b}}_{\mathrm{t}_i} = \sum_{k=1}^{n} t_{ik}$ and $P^{\mathrm{b}}_{\mathrm{h}_i} = \sum_{k=1}^{n} t_{ik}$. Similarly, the total active load at bus k supplied by bilateral transactions is $P^{\mathrm{b}}_{\mathrm{d}_k} = \sum_{i=1}^{n} t_{ik}$. Thus, the value of the transaction between the generator at bus i and the load at bus k is limited by the generation capacity and by the value of the demand supplied in the bilateral market, that is,

$$0 \leqslant t_{ik} \leqslant t_{ik}^{\max} = \min\{P^{\max}_{g_i}, P^{\mathrm{b}}_{\mathrm{d}_k}\}, \tag{2}$$

where $P^{\max}_{g_i}$ is the maximum active generation capacity of a thermal or a hydro generator.

For a planning horizon ranging from one to seven days, divided into np time periods that correspond to the number of market clearings and generation re-dispatch, a set of transaction matrices $\mathbf{T}_j$, $j = 1, \dots, np$ is defined. Since, usually, not all the buses participate on the transactions, some elements of $\mathbf{T}_j$ are zero. Therefore, the power transactions are represented through a column vector $\mathbf{t}_j$ with the number of lines equal to the number of nonzero elements of $\mathbf{T}_j$. Using this vector, we can define the vectors of bilateral thermal and hydro active generation, $\mathbf{P}^{\mathrm{b}}_{\mathrm{t}_j}$ and $\mathbf{P}^{\mathrm{b}}_{\mathrm{h}_j}$, and the vector of bilateral loads, $\mathbf{P}^{\mathrm{b}}_{\mathrm{d}_j}$, as

$$\begin{aligned} \mathbf{P}^{\mathrm{b}}_{\mathrm{t}_j} &= \mathbf{U}_{\mathrm{t}} \cdot \mathbf{t}_j, \\ \mathbf{P}^{\mathrm{b}}_{\mathrm{h}_j} &= \mathbf{U}_{\mathrm{h}} \cdot \mathbf{t}_j, \\ \mathbf{P}^{\mathrm{b}}_{\mathrm{d}_j} &= \mathbf{U}_{\mathrm{d}} \cdot \mathbf{t}_j, \end{aligned} \tag{3}$$

where $\mathbf{U}_{\mathrm{t}}$, $\mathbf{U}_{\mathrm{h}}$ and $\mathbf{U}_{\mathrm{d}}$ are incidence matrices that associate the bilateral transactions to the thermal and hydro generators and to the loads.

We can also define vectors composed of the active generation and loads traded with the pool at the spot market price, $\mathbf{P}^{\mathrm{p}}_{\mathrm{t}_j}$, $\mathbf{P}^{\mathrm{p}}_{\mathrm{h}_j}$ and $\mathbf{P}^{\mathrm{p}}_{\mathrm{d}_j}$. Thus, if $\mathbf{P}_{\mathrm{d}_j}$ is the vector of the total bus active loads at time period j, we have:

$$\mathbf{P}_{\mathrm{d}_j} = \mathbf{P}^{\mathrm{p}}_{\mathrm{d}_j} + \mathbf{U}_{\mathrm{d}} \cdot \mathbf{t}_j. \tag{4}$$

In addition, taking into consideration the generation capacity of the thermal and hydro generation units, we have:

$$\begin{aligned} \mathbf{P}^{\min}_{\mathrm{t}} &\leqslant \mathbf{P}^{\mathrm{p}}_{\mathrm{t}_j} + \mathbf{U}_{\mathrm{t}} \cdot \mathbf{t}_j \leqslant \mathbf{P}^{\max}_{\mathrm{t}}, \\ \mathbf{P}^{\min}_{\mathrm{h}} &\leqslant \mathbf{P}^{\mathrm{p}}_{\mathrm{h}_j} + \mathbf{U}_{\mathrm{h}} \cdot \mathbf{t}_j \leqslant \mathbf{P}^{\max}_{\mathrm{h}}, \end{aligned} \tag{5}$$

where $\mathbf{P}^{\min}_{\mathrm{t}}$, $\mathbf{P}^{\min}_{\mathrm{h}}$, $\mathbf{P}^{\max}_{\mathrm{t}}$ and $\mathbf{P}^{\max}_{\mathrm{h}}$ are vectors composed of the minimum and maximum thermal and hydro active generation limits.

If we consider the bus voltages equal to 1.0 pu, the vector of active power flows at time period j, $\mathbf{f}_j$, can be expressed as a nonlinear function of the bus voltage angles and the series impedance of the lines and transformers, that is,

$$\mathbf{f}_j = \mathbf{f}_j(\boldsymbol{\delta}_j), \tag{6}$$

where $\boldsymbol{\delta}_j$ is the vector of bus voltage angles at time interval j. Using the same supposition, the active power balance equations of the system can be written as

$$(\mathbf{P}^{\mathrm{p}}_{\mathrm{t}_j} + \mathbf{U}_{\mathrm{t}} \cdot \mathbf{t}_j) + (\mathbf{P}^{\mathrm{p}}_{\mathrm{h}_j} + \mathbf{U}_{\mathrm{h}} \cdot \mathbf{t}_j) - (\mathbf{P}^{\mathrm{p}}_{\mathrm{d}_j} + \mathbf{U}_{\mathrm{d}} \cdot \mathbf{t}_j) = \mathbf{P}_j(\boldsymbol{\delta}_j), \tag{7}$$

where $\mathbf{P}_j$ is the vector of active power injections.