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A dynamic regrouping based sequential dynamic programming algorithm for unit commitment of combined heat and power systems

Aiying Rong [a,*], Henri Hakonen [b], Risto Lahdelma [b]

[a] Technical University of Denmark, Department of Management Engineering, Produktionstorvet 425, 2800 Kgs., Lyngby (Copenhagen), Denmark
[b] University of Turku, Department of Information Technology, Joukahaisenkatu 3, FIN-20520 Turku, Finland

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ABSTRACT

This paper addresses the unit commitment (UC) in multi-period combined heat and power (CHP) production planning under the deregulated power market. In CHP plants (units), generation of heat and power follows joint characteristics, which implies that it is difficult to determine the relative cost efficiency of the plants. We introduce in this paper the DRDP-RSC algorithm, which is a dynamic regrouping based dynamic programming (DP) algorithm based on linear relaxation of the ON/OFF states of the units, sequential commitment of units in small groups. Relaxed states of the plants are used to reduce the dimension of the UC problem and dynamic regrouping is used to improve the solution quality. Numerical results based on real-life data sets show that this algorithm is efficient and optimal or near-optimal solutions with very small optimality gap are obtained.

1. Introduction

Combined heat and power (CHP) production means the simultaneous production of useful heat and electric power. Compared to separate generation of heat in boilers and power in condensing plants, CHP systems offer considerably higher energy efficiency levels (up to 90 %) than conventional separate power production. This leads to fuel (and emissions) savings of typically between 10–40% [1]. Therefore, CHP production is considered a leading technology to respond to the market demand and environmental concerns [2]. To improve the competitiveness of a CHP system in the deregulated power market, efficient, accurate and robust tools for optimization of the unit commitment (UC) and economic dispatch (ED) have to be developed. The goal in the combined UC and ED problem is to determine when to start up and shut down the plants and how to dispatch the committed units to meet (forecast) demand and other constraints cost-efficiently.

The interdependence between power and heat generation in CHP plants imposes difficulty for production planning. The ED alone is much more complicated for CHP systems than for power-only generation systems [3,4]. The UC of medium-sized energy companies (up to 20 plants [5–8]) is difficult to solve satisfactorily. This may be one of the major reasons why the literature on UC of CHP systems is scant in contrast to the rich literature on UC of power-only generation systems (see e.g. extensive reviews in [9,10]).

Currently, the solution approaches to UC of CHP systems are limited to some general-purpose methods. The research follows two lines. The first line applies decomposition techniques such as Lagrangian relaxation (LR) [11,12] and dynamic programming (DP) based algorithms [6,7,13]. The second line treats the overall problem as an entity and resorts to a general solver (possibly with some modifications) such as the Branch and Bound algorithm [14] for solving a mixed integer linear programming (MILP) formulation of the problem. The application of simulation approaches [15,16] and artificial intelligent techniques such as genetic algorithms [17] should be placed under this category. It is undoubted that the interior point method (IPM) [18] and the improvement of the formulation for the UC problem [19] can also be applied to CHP systems.

Based on different application backgrounds, the CHP plant characteristics can be represented as linear programming (LP) or MILP models [5,20–24] or as non-linear programming (e.g. quadratic programming) models [4,11,25]. In this paper we adopt LP/MILP-based modeling techniques. The benefit of LP-based models is that there are reliable and quite efficient algorithms such as Simplex algorithms [26] and IPM [27] for solving the ED problems. In conjunction with specialized modeling techniques for certain application contexts, some extremely efficient algorithms for solving the structured LP/MILP problems have been developed [23,28]. These algorithms are part of commercial EHTO/GENRIS energy information systems developed by Process Vision Ltd. (a Finnish energy information system company) [24]. To deal with the UC problem satisfactorily, we need to utilize efficient LP solvers intelligently.

In this paper we apply a DP-based decomposition approach for solving the UC of the CHP planning problem. The reason for

* Corresponding author. Tel.: +45 45254768; fax: +45 45256005.
E-mail addresses: aiying.rong@gmail.com, ar@ipl.dtu.dk (A. Rong).

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Nomenclature

Index sets
- J set of extreme points of the operating regions of all components including both physical and non-physical plants (e.g. contracts), $J = \bigcup_{u \in U^*} J_u$
- J_u set of extreme points of the operating region of component $u \in U^*$
- U set of all physical plants
- U^* set of all components including both physical and non-physical plants

Indices
- j extreme point index
- j_u^{OFF} index of extreme point corresponding to OFF-state of plant u, $j_u^{\mathrm{OFF}} \in J_u$
- t period index
- u plant index

Parameters
- $(c_{j,t}, p_{j,t}, q_{j,t})$ extreme point $j \in J_u$ of the operating region (cost, power, and heat) of component $u \in U^*$ in period t
- $c_{p+,t}$, $c_{p-,t}$ power sales/purchase price on the market in period t
- $c_{q+,t}$ penalty cost for heat surplus in period t
- $s_u(w_{u,t-1}, y_{u,t})$ start-up and shut-down cost function for plant $u \in U$ in period t
- P_t power demand in period t
- Q_t heat demand in period o
- T number of periods in planning horizon
- Y_u^{OFF} Set of periods when component $u \in U^*$ is at forced OFF-state
- Y_u^{ON} set of periods when component $u \in U^*$ is at forced ON-state
- $\tau_u^{UP}, \tau_u^{\mathrm{DOWN}}$ minimum up and down time for plant $u \in U$ after start-up and shut-down
- τ_u^{COLD} Cold start-up time for plant $u \in U$

Variables
- $w_{u,t}$ state variable for plant u, indicating number of periods that plant $u \in U$ has been on or off at the end of period t (negative values denote off-time). The initial states $w_{u,0}$ are given
- $x_{j,t}$ variables encoding the operating level of each component u in terms of extreme points $j \in J_u$ in period t
- $x_{p+,t}$, $x_{p-,t}$ power sales and purchase volume on the power market in period t
- $x_{q+,t}$ heat surplus variable for period t
- $y_{u,t}$ zero-one decision variable indicating whether component $u \in U^*$ is OFF or ON in period t
- $\lambda_{p,t}$, $\lambda_{q,t}$ dual price for power and heat in period t based on the solution to the state-relaxed problem
- $C_{u,t}$ operating cost of plant u in period t
- $P_{u,t}$ power generation of plant u in period t
- $Q_{u,t}$ heat generation of plant u in period t

Notations used in the DRDP-RSC algorithm
- I number of iterations for the inner loop
- K number of iterations for the outer loop, K = 1 or 2
- m_G Maximum number of plants committed together
- N maximal number of plants committed together, based on the heap size of the programming software.
- R_u^R heuristic relative cost measure for plant u based on the solution to the state-relaxed problem.
- U_c ordered set of plants that have been committed
- U_m ordered set of plants committed together
- U_1 temporary ordered set used in the algorithm

choosing the decomposition approach is that certain analyses (such as risk analysis on the competitive market [29–33]) require quite long planning horizons (at least a month with hourly periods), and in such tasks the decomposition techniques are much more favorable than treating the overall problem as an entity. Even though the LR schemes are among the most widely used decomposition techniques to deal with UC problems [9,10], we choose the DP-based algorithm, because it is more robust than the LR algorithm. It is widely known that the traditional subgradient based LR algorithm suffers from convergence difficulties especially with LP-based models [34]. Some advanced techniques such as the bundle method [35] can find better search directions than the subgradient method and guarantee the convergence of the LR algorithm. However, the bundle method requires much more sophisticated techniques and computational effort to obtain the proper search directions.

One restriction for DP-based algorithms is that it is difficult to consider power ramp constraints for CHP plants. Power ramp constraints have historically eluded efficient exact DP approaches. This has recently changed for power-only generation plants. Ref. [36] presented a DP algorithm for a single-unit UC problem. This algorithm needs first to solve multiple multi-period ED problems with power ramp constraints optimally. Then the optimal power generation level in each period can be obtained based on ramp-up and ramp-down limits by an induction procedure. For a single-unit UC problem, the authors show that time complexity of the DP algorithm is $O(n^3)$ (n is the number of periods over the planning horizon). However, for CHP plants, restriction on power generation levels leads to restriction on heat generation levels and the determination of both power and heat generation level become quite complicated [37] because of the interdependence between power and heat generation in CHP plants. It means that it becomes computationally expensive to determine both power and heat generation level optimally for considering power ramp constraints for CHP plants. Here we choose to ignore power ramp constraints. Ignoring ramp constraints does not pose a serious problem in some application settings, e.g. for a long-term risk analysis.

To make DP-based algorithms solve problems of practical size, the dimension of the problem must be reduced because the pure DP algorithm suffers from the "curse of dimensionality", which may result in unacceptable solution time [9,10]. In power-only generation systems the dimension is typically reduced based on a priority list formed using the marginal power production costs. This approach is much more difficult in CHP planning, because the marginal production costs for both heat and power depend on both the heat and power production levels, and these levels vary from hour to hour.

For CHP systems, [13] introduced a general DP scheme based on relaxed ON/OFF states of plants and sequential commitment of subsets of plants to reduce the dimension. We call it the relaxation and sequential commitment (DP-RSC) scheme. When a plant is at relaxed state, the ON/OFF state variable can be temporarily excluded from the set of variables. Therefore, the dimension of the UC problem can be reduced by setting temporarily some plants to relaxed states. Then the ON/OFF combinations of fewer plants need to be considered simultaneously. The ON/OFF states of the re-