Electric Power Systems Research 86 (2012) 98–112

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Generation Expansion Planning by MILP considering mid-term scheduling decisions

Grigorios A. Bakirtzis, Pandelis N. Biskas*, Vasilis Chatziathanasiou

Department of Electrical Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

ARTICLE INFO

Article history:
Received 13 May 2011
Received in revised form 5 October 2011
Accepted 8 December 2011
Available online 4 January 2012

Keywords:
Generation Expansion Planning
Mixed-Integer Linear Programming
Value of lost load
Optimal planning
Optimal unit maintenance schedules
Mid-term scheduling decisions

ABSTRACT

This paper presents a mixed-integer linear programming model for the solution of the centralized Generation Expansion Planning (GEP) problem. The GEP objective is the minimization of the total present value of investment, operating and unserved energy costs net the remaining value of the new units at the end of the planning horizon. Environmental considerations are modeled through the incorporation of the cost of purchasing emission allowances in the units' operating costs and the inclusion of annual renewable quota constraints and penalties. A monthly time-step is employed, allowing mid-term scheduling decisions, such as unit maintenance scheduling and reservoir management, to be taken along with investment decisions within the framework of a single long-term optimization problem. The proposed model is evaluated using a real (Greek) power system. Sensitivity analysis is performed for the illustration of the effect of demand, fuel prices and CO_2 prices uncertainties on the planning decisions.

1. Introduction

Investment decisions are ubiquitous and have always posed great interest to economists, analysts and researchers, considering optimal investment strategies for the optimal siting, timing, sizing and type of an investment. Investments on energy production capacity are characterized by:

(1) *Partial or complete irreversibility*: the prospective investor cannot disinvest should the market conditions change adversely. The initial cost of investment is sunk; it cannot be recovered in total.
(2) High risks, concerning (a) the ongoing uncertainty of the economic environment in which the decisions are made, and (b) possible regulatory decisions that may affect the expected income/amortization of the unit.

The classical problem that has been employed by researchers for managing the above risks is the Generation Expansion Planning (GEP) problem. Its solution determines the capacity addition schedule (siting, timing, sizing and technology of new plant additions) that satisfies forecasted load demand within given reliability criteria over a planning horizon of typically 10–30 years. In its extended formulation, GEP is a large-scale highly constrained mixed-integer non-linear programming (MINLP) problem, the global optimum of which can be reached only by complete enumeration. Thus, the determination of the proven optimal solution would require the investigation of every possible combination of candidate options over the planning horizon. The enormous calculation overhead of such an approach has forced researchers to employ simplifications of the analytical model and solve it using several sophisticated optimization methods and meta-heuristics during the past decades.

Two modeling approaches have been developed for the solution of GEP: (a) the micro-approach, and (b) the macro-approach [1]. The micro-approach employs analytical and sophisticated methods of operational research and meta-heuristics to cope with complex non-linear transmission constraints and reliability criteria. In micro-approach, the GEP data are set at high level of detail; nevertheless, global optimality cannot be guaranteed. The micro-approach however deals with a problem that is part of a greater macro-economic framework, which considers the planning of the whole economy/energy system based on multi-sector scenarios. Macro-economic approaches reduce the modeling complexities, i.e. ignore the complex features and constraints within the energy sector, usually resulting in linear programming (LP) models. The results of macro-approach models are always macroscopic and rough [1–3].

The literature on the solution of the GEP problem using micro-approach modeling is extensive. Two classes of problems have been

* Corresponding author at: Power Systems Laboratory, Division of Electrical Energy, Department of Electrical Engineering, Aristotle University of Thessaloniki, AUTh Campus, 54124 Thessaloniki, Greece. Tel.: +30 2310 994352; fax: +30 2310 996302.
E-mail address: pbiskas@auth.gr (P.N. Biskas).

0378-7796/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsr.2011.12.008

considered: (a) the centralized approach, and (b) the decentralized approach.

In the centralized approach, the GEP problem is solved centrally:

(a) in monopoly situations, by a state-owned or private monopoly-utility to determine the least-cost expansion planning, and
(b) in a deregulated market, by governing or regulating authorities, in order to formulate market designs and policies that lead to the long-term targets of a country (giving motives to certain technologies), concerning the minimization of the overall cost of supplying electricity to the end consumers, the penetration of renewable energy sources, the CO_2 emission control, as well as the interactions between emission trading and renewable support schemes, namely the impact of a variety of emission caps and RES support schemes both individually and combined.

Several methods have been developed for the solution of the centralized problem, such as stochastic dynamic programming [4], non-linear programming (NLP) [5], mixed-integer linear programming (MILP) [6], multi-objective programming [7], evolutionary programming (e.g. GAs) [8–15], and other heuristics and mathematical approaches [16–18]. The formulation of the problem objective and constraints varies in each implementation, incorporating emissions costs and other environmental constraints (NO_x, SO_x), transmission constraints, reliability criteria, demand-side management programs, reserve margins, location and financial constraints. An overview of the basic features of these approaches is presented in Table 1.

In [4] a stochastic dynamic programming model is presented for the solution of the centralized GEP problem, considering uncertainties in demand and fuel prices. The uncertain variables are modeled by Markov chains. In [5] a non-linear programming approach is presented, with a detailed operation model for pumped/storage hydro units and a realistic model of capital costs for hydro plants. The NLP solver "MINOS" is employed for the solution of the relevant problem. In [6] an integrated analysis of GEP and financial planning is provided. All financial constraints are incorporated to the GEP problem, which is formulated as a MIP model. Scenario-based (sensitivity) analysis is employed for the evaluation of several financial planning options. In [7] a multi-objective (multi-criteria) linear programming method is developed incorporating transmission constraints with a DC network representation. The four objectives comprise (a) the investment, operational and transmission costs, (b) the environmental impact, (c) the imported fuel, and (d) the energy price risks. In [8] evolutionary programming is employed to handle the nonlinearity introduced by the reliability criterion (Loss of Load Probability, LOLP). A mixed-integer bilinear multi-objective evolutionary programming model is presented in [9], with combined investment decisions for generation and transmission expansion. Scenario-based analysis is used to evaluate the effect of fuel prices on the different objectives. In [10] several metaheuristic techniques are applied and compared for the solution of the GEP problem. In [11–15] Genetic Algorithms are employed, for the solution of either the single-objective or the multi-objective GEP. Ref. [13] is the only approach handling an AC network representation. GA-based approaches can handle the nonlinearity introduced by the LOLP reliability criterion and claim to have the ability to locate the global optimum of the GEP problem within a reasonable computation time. However, they have some structural problems when applied to large-sized problems, such as premature convergence to a local optimum. Finally, several heuristics and mathematical programming approaches have been presented in the literature for the solution of the GEP problem, such as a simple probabilistic peak-shaving method in [16], a heuristic algorithm handling transmission constraints in [17] and a multi-objective optimization model with Monte-Carlo simulation for demand and unit availability uncertainty in [18].

Integrated software packages have also been developed for the solution of the centralized GEP, e.g. the well-known WASP-IV (Wien Automatic System Planning) [19], developed by the International Atomic Energy Agency (IAEA), in which dynamic programming is employed to determine a least cost generation capacity addition plan under specified LOLP target.

In the decentralized approach, the strategic GEP problem decision making of a producer within a deregulated (usually oligopolistic) market framework is considered. These models are more complex, since the market operation, and the behavior of rival producers must be modeled appropriately. Game theory is employed for the formulation of nearly all such models, which are solved using stochastic dynamic programming [20–21], Lagrangian relaxation, Benders decomposition [22], evolutionary programming [23,24], iterative search methods [25], system dynamics [26], heuristic methods [27], and by Mathematical Program with Equilibrium Constraints (MPEC) solvers [28,29]. Each of these methods has its pros and cons; an analytical review and comparison of most of the above methods can be found in [29].

The common feature of all the above-mentioned works is that a yearly or two-year time-step is considered during the planning horizon. Only in [21,22] a seasonal step (four seasons per year) is used. These time-steps are not able to incorporate mid-term scheduling aspects in the long-term planning framework. However, the incorporation of mid-term scheduling decisions, such as the maintenance scheduling of existing and new units, plays a significant role in the provided solution, and may alter significantly the results (e.g. reliability indices), especially during peak-load periods.

In this paper the centralized GEP problem is formulated and solved as a mixed-integer linear programming (MILP) problem. The system reliability criterion is implicitly modeled by embedding in the problem objective function the cost of the load not served (LNS), valued at the value of lost load (VLL). Environmental aspects are modeled through (a) the incorporation of the cost of purchasing emission allowances in the thermal unit operating cost, similarly with the short-term optimization modeling presented in [30,31], and (b) the inclusion of annual renewable quota constraints and penalties. In addition, a maximum RES penetration constraint is used to model operational reliability requirements. A monthly time-step is employed, allowing the consideration of unit maintenance schedules in the optimization problem. It is assumed that each unit undergoes a one-month outage for maintenance during every year. The GEP algorithm optimizes the maintenance schedules of both existing and new units, along with the optimization of the new capacity additions. The refurbishment of existing units is efficiently modeled. At the end of the useful life of a generating unit a refurbishment decision may be taken. A refurbishment cost is involved, which potentially (a) decreases the total variable cost of the unit, (b) increases the unit capacity, (c) reduces the unit FOR and (d) extends the expected lifetime of the unit. In this way, the conversion of Open-Cycle Gas Turbines to Combined-Cycle Gas Turbines, the conversion of coal/lignite units to low-carbon coal units with carbon capture and storage systems, or other environmental improvements are modeled efficiently.

The proposed model is evaluated using a real (Greek) power system. Scenario-based (sensitivity) analysis is performed for the illustration of the effect of demand, fuel prices and CO_2 prices uncertainties on the planning decisions. As shown in Table 1, there are three methods to account for stochastic parameters, as follows:

(a) scenario-based (sensitivity) analysis, which is used by the most approaches reported in the literature ([6,9,21,23,27,29], and also in this paper),