ARTICLE IN PRESS

Renewable Energy xxx (2016) 1–9

Contents lists available at ScienceDirect

Renewable Energy

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

A multi-period unit commitment problem under a new hybrid uncertainty set for a renewable energy source

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ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
4 February 2016
Accepted 31 May 2016
Available online xxx

Keywords:
Robust optimization
Unit commitment
Optimization under uncertainty

ABSTRACT

Recently, there is a growing use of renewable energy in the electricity markets due to governmental subsidy aiming to comply with reduced greenhouse gas emission targets. Jointly with its highly volatile generation it greatly affects the operation planning of power plants, particularly, when addressing the unit commitment problem (UCP).

The UCP is imperative in electric power system operations. It seeks an operating policy for a system of generating units over a multi-period finite horizon to meet the demand, subject to equipment and physical constraints. We consider a profit based UCP (PUCP) of an energy producer operating in a deregulated market aiming to maximize its profit facing uncertainty in both market price and wind generation. Here, we employ the robust optimization (RO) methodology which provides a feasible solution for any realization of the uncertain parameters within a bounded set, resulting in a *guaranteed* value of the objective function. This leads to a model, which is a bilinear mixed integer problem.

The method we develop in this paper results in a problem, which is notably as difficult to solve without uncertainty. Furthermore, its resulting policy is more successful in meeting the demand for electricity than that of currently used methods.

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1. Introduction

Lately, the reduction of greenhouse gas emission has become a worldwide goal. Consequently, an increasing number of governments choose to subsidize the generation of renewable energy. Therefore, the renewable energy share in the electricity markets is intensively growing. Typically, the markets' regulator determine the production plan of every generating system in the market, such that the renewable energy generation will be fully consumed by the market before conventional power plant's generation is taken into account. Furthermore, such renewable energy generation is usually very volatile and hence highly uncertain. Accordingly, the operation planning of power plants is greatly affected by the integration of renewable energy into the market, particularly, when considering the unit commitment problem.

The unit commitment problem (UCP) objective is finding an economic generation and operation policy of a system of generating units, subject to device and operating constraints, in order to meet the forecasted power demand. This policy determines, at every time period of the planning horizon, which units to operate (commit), and the generation of each of the active units. The latter decisions are often referred to in the literature as *economic dispatch*. Typically, the UCP is a mixed integer and linear program (MILP), where the commitment decision variables are integer and the objective function and constraints are linear in both the commitment and the dispatch decision variables.

Recently, the UCP faces new challenges due to increasing uncertainties in demand and supply, caused by price responsive demand and the integration of renewable energy generation, such as wind power. Typically, both demand and price have a similar cyclic daily pattern that changes over the yearly seasons and differs only in magnitude. Likewise, the wind power is characterized by a particular seasonal cyclic daily pattern.

Stochastic programming (SPR) is a common method to model the UCP in the presence of uncertainty [1–4]. This approach assumes full knowledge of the probability distribution, and aims at maximizing expected profit [5,6]. Two such approaches are: i) Two-stage SPR, where the first stage decisions are the commitment ones and the second stage decisions are the economic dispatch ones. ii)

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http://dx.doi.org/10.1016/j.renene.2016.05.095
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Please cite this article in press as: M. Melamed, et al., A multi-period unit commitment problem under a new hybrid uncertainty set for a renewable energy source, Renewable Energy (2016), http://dx.doi.org/10.1016/j.renene.2016.05.095

Nomenclature

Parameters

T	number of time periods in the planning horizon
TE	thermal unit's thermal electric energy conversion efficiency
TPL	minimum quantity of thermal power to operate the thermal unit boiler
TPU	maximum quantity of thermal power to operate the thermal unit boiler
UT	minimum operation time periods of the thermal unit
DT	minimum shutdown time periods of the thermal unit
IU	initial time periods where the unit must be on
ID	initial time periods where the unit must be off
c_i	thermal power price of supplier i
FSU_i	maximum thermal power available from supplier i
L	prior obligation of delivery according to a long term contract

Decision variables

z_t	binary decision variable indicating whether the thermal unit is on or off
$q_{i,t}$	thermal power purchased from supplier i at period t

Uncertainty decision variables

w_t	wind generation at period t
p_t	electricity spot price at period t
ε	trend factor affecting the price trajectory
θ	price's trend factor weight
ζ	price's periodic factor's trajectory
δ	trend factor affecting the wind generation trajectory
φ	wind generation's trend factor weight
ξ	wind generation's periodic factor's trajectory

Uncertainty sets

$\mathscr{P}_\cdot$	Novel uncertainty set of the price
$\mathscr{W}_\cdot$	novel uncertainty set of the wind generation
$\overline{\mathscr{P}}_\cdot$	new hybrid uncertainty set of the price
$\overline{\mathscr{W}}_\cdot$	new hybrid uncertainty set of the wind generation

Multi-stage SPR extended the former approach into multi-stage and is solved using dynamic programming (DP) from the last period backwards. Typically this type of problem is limited to very few periods otherwise the event tree explodes exponentially [7]. The most common method applied to two-stages SPR problems is the Benders' decomposition (BD) method [8,9] that projects the original problem to the space of the integer variables such that it is divided into a master problem and its subproblem. This method converges under different sets of conditions, and terminates in a finite number of steps. Another method is the Lagrangian relaxation (LR) [10], that deals with constraints that couples continuous and integer variables. LR removes theses constraints from the UC model [11] and move it into the objective function multiplied by a fixed Lagrange multiplier. The solution to this new model is near optimal and strongly depend on the Lagrange multiplier value.

Another method that overcome the SPR intractability uses approximation, namely the known sample average approximation (SAA), which was introduced in Ref. [12]. The SAA is a Monte Carlo simulation based approach with the basic idea of generating a random sample and approximate its expected value function by the corresponding sample average function [13–15]. We refer to this method as MC.

Lately, the robust optimization (RO) approach [16–18] was applied to the UCP, for example see [19,20] and many others. The RO methodology uses a max-min approach to obtain a solution, which is feasible for all the realizations within a predefined *uncertainty set*. It provides a guaranteed lower bound on the objective function value over all these realizations. The robust solution immunity against all realization that might occur within the uncertainty set is critical in the electricity generation systems.

Indeed, electricity as an energy source is essential for the functional operation of the economy, water supply system, various military systems, hospitals and more. Yet, there is no commercial viability of electricity storage system (excluding pumped energy facilities), so there is almost no practical ability to store electricity for later use. Therefore, electricity is considered a vital resource, and the impact of unsatisfied demand is crucial and could not be tolerated. Consequently, the risk of operating a system of generating units should be minimized, which is inherent in the RO methodology.

The RO approach is seemingly considered "conservative", see for example [21]. Nevertheless, in this paper we empirically show that, in fact, the RO solution exhibits superior worst-case performance and exceptionally lower variance than practiced methods. Furthermore, it also yield a preferred service level, i.e., proportion of successfully meeting the demand for electricity.

In the classical UCP settings, a central body controls the generation, transmission and distribution of the electric energy, and as a results it aims to minimizes its costs [22]. However, in a deregulated market these three activities are separated. Therefore, each generator objective is to maximize its own total profit (revenue minus operational costs), without the necessity of serving the demand. This problem is known in the literature as the profit based unit commitment problem (PUCP) [23,24]. Note that the PUCP is indirectly affected by the uncertain demand, which is expressed in the market (spot) price.

In this study we employ a multi-stage offline RO method, namely the robust counterpart (RC), to a PUCP of a local generator operating one thermal unit and a wind energy source under uncertain price and uncertain wind power. The RC method is an offline method where all the decisions should be made at the outset of the horizon, before the uncertain data is revealed. One may think of the data as being picked by an adversary, with limited power, to minimize the decision maker's profit (adversary problem), whereas the decision maker wishes to maximize its profit given this chosen data (decision maker's problem).

To capture the seasonally cyclic daily pattern of the uncertain trajectories of the price and wind power we suggest a new uncertainty set structure for both, such that for each period the uncertain value is bounded within lower and upper bounds, and is affected by both a periodic factor and a trend factor. The latter affects each one of the uncertain trajectory values to keep the known pattern, whereas the former affects only that same period to express volatility. We assume that the trend factor belongs to a predefined interval, and the trajectory of the periodic factors belongs to an arbitrary norm.

Unfortunately, the RC problem associated with the aforementioned uncertainty set is intractable. However, given the trend factors' values, the RC problem can be solved for meaningful cases. Therefore, we define a new hybrid uncertainty set, in the sense that

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