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Evaluating the effectiveness of normal boundary intersection method for short-term environmental/economic hydrothermal self-scheduling

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ABSTRACT

The problem of the optimal scheduling of available hydro and thermal generating units considering a short scheduling period (one day-one week) in order to maximize the total profit is denoted as short-term hydro thermal self-scheduling (SHTSS). Mixed-integer linear programming (MILP) method is proposed to model the SHTSS problem in the day-ahead energy and reserve markets. MILP formulation allows for considering a precise model for the prohibited working zones, dynamic ramp rate constraints and operating services of thermal generating units, as well as the characteristics of multi-head power discharge for hydro generating units and reservoirs' spillage. This problem is modelled as a multi-objective (MO) optimization one, having two objectives, i.e. maximization of the profit of Generation Company's (GENCO's) and minimization of emissions from thermal units. In order to solve the problem and generate the non-inferior solutions, normal boundary intersection (NBI) method is applied. The main advantage is the provision of set of uniformly distributed non-dominated solutions regardless of the scales of objective functions values. Then, a fuzzy based decision maker is employed in order to select a non-inferior solution. In order to demonstrate the effectiveness of the presented method, several numerical simulations are presented. Furthermore, the obtained results are compared with those obtained considering different methods for obtaining non-inferior solutions, such as weighted sum method, evolutionary programming-based interactive fuzzy satisfying method, differential evolution, particle swarm optimization and hybrid multi-objective cultural algorithm.

1. Introduction

Determining the optimal schedule of available generating units (hydro and thermal generators) over a scheduling period (one day–one week) that minimizes the total operating costs is defined as short-term hydro thermal scheduling (SHTS) [1,2]. On the contrary, in short-term hydro thermal self-scheduling (SHTSS), hydro and thermal generating units are used so that the total profit is maximized [3,4]. Different optimization methods for the SHTS problem have been presented in literature.

In this regard, the application of the mixed-integer linear programming (MILP) method for solving SHTSS problems in day-ahead market has been proposed in [3,4] in which a deterministic optimization framework is used to model the problem and the expected profit is maximized employing 0/1 MILP technique. In order to precisely model hydro units, the characteristics of multi-head power discharge relating to hydro generating units have been presented in [4,5] while MILP method has been utilized to maximize the profit. Mandal and Chakraborty [6] has studied the control parameters for optimal hydro thermal scheduling based on differential evolution. The SHTS problem has been solved in [7] using teaching–learning based optimization method while nonlinearities of hydro units' reservoirs have been considered. In addition, Liao et al. [8] has solved the SHTS problem employing adaptive bee colony method and chaotic exploration to efficiently avoid a local optimum. A

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Nomenclature

Indices

i	thermal generating units index
j	hydro generating unit index
t	time interval (hour) index

Constants

π_t^b	bilateral contract price at time t (\$/MWh)
π_t^{ns}	market price of non-spinning reserve (\$/MWh)
π_t^s	market price for energy at time t (\$/MWh)
π_t^{sr}	market price of spinning reserve at time t (\$/MWh)
η	conversion factor which is $3.6{*}10^{-3}$ ($\mathrm{Hm}^3\ \mathrm{s/m}^3\ \mathrm{h}$)
Θ	number of time steps of the scheduling period
$\underline{\theta}_{j,t}$	lower bound of water discharge pertaining to the hydro generating unit j at time t (m^3/s)
$\bar{\theta}_{j,t}$	upper bound of water discharge pertaining to the hydro generating unit j at time t (m^3/s)
τ_{ij}	time interval among reservoir of hydro generating unit i and hydro generating unit j (h)
A_i	cost of shut down pertaining to the thermal generating unit i (\$)
A_j	cost of start-up pertaining to the hydro generating unit j (\$)
$b_{n,i}$	nth block's slope pertaining to the cost curve of the thermal generating unit i (\$/MWh)
b_n,j	slope of the block n pertaining to the reservoir of the hydro generating unit j ($\mathrm{m}^3/\mathrm{s}/\mathrm{Hm}^3$)
$b_{n,j}^k$	nth block's slope relating to the performance curve k of hydro generating unit j ($\mathrm{MW}/\mathrm{m}^3/\mathrm{s}$)
$be_{n,i}$	nth segment's slope relating to the emission curve of the thermal generating unit i (lb/MWh)
D	objective function of the NBI method
$e_{\mathrm{min},i}$	minimum emission generated by thermal generating unit i (lb)
EGR	emission group including SO_2 and NO_x
$E(p_{n-1,i}^u)$	emission generation relating to the $n-1$th superior limit in emission curve belonging to the thermal generating unit i (lb)
$F(p_{n-1,i}^u)$	generation cost relating to the $n-1$th superior limit in cost curve belonging to the thermal generating unit i (\$/h)
$F_{\mathrm{j,t}}$	the predicted value for the natural water inflow relating to the reservoir of the hydro generating unit j at time t (Hm^3/h)
$K^{\lambda}{}_i$	cost relating to the discrete interval λ of the start-up cost pertaining to the thermal generating unit i (\$/h)
$I^0{}_i$	ith thermal generating unit's initial status (0/1)
L	number of variable heads
M	number of not-allowed operating zones
N	number of blocks relating to the piecewise linearized hydro generating unit's performance curve
NB	number of bilateral contracts
NE	number of blocks relating to the piecewise linearized thermal generating unit's emission curve
NL	number of blocks relating to the piecewise linearized variable cost function
p_t^b	power capacity relating to the bilateral contract at time t (MW)
$p_{min,\mathrm{i}}$	minimum power relating to the ith thermal generating unit (MW)
$p_{max,i}$	maximum power relating to the ith thermal generating unit (MW)
$\underline{p}_{n,j}$	minimum power relating to the jth hydro generating unit for the nth performance curve (MW)
$\bar{p}_j$	jth hydro generating unit's capacity (MW)
$p_{n,i}^d$	lower bound of the prohibited operating zone n pertaining to the ith thermal generating unit (MW)
$p_{n-1,i}^u$	upper bound of the prohibited operating zone $n-1$ pertaining to the ith thermal generating unit (MW)
$\underline{Q}_j$	minimum water discharge relating to the jth hydro generating unit, provided that it is on (m^3/s)
$\bar{Q}_{n,j}$	maximum water discharge relating to the nth block of the jth hydro generating unit (m^3/s)
$RDL_{n,i}$	ramp down limit relating to the nth block (MW)
$RUL_{n,i}$	ramp up limit relating to the nth block (MW)
$s^0{}_i$	number of time periods during which the ith thermal generating unit was shut down at the start of the planning horizon (h)
$\bar{s}_j$	maximum spillage relating to the jth hydro generating unit (m^3/s)
$s_{max,\mathrm{i}}$	maximum hours that the ith thermal generating unit can be off (h)
SUE_i	emission generation of the ith thermal generating unit when started-up (lb)
SDE_i	emission generation of the ith thermal generating unit when shut down (lb)
SD_i	limit of shut down ramp rate relating to the ith thermal generating unit (MW/h)
SU_i	limit of start-up ramp rate relating to the ith thermal generating unit (MW/h)
UT_i	minimum up time relating to the ith thermal generating unit (h)
$U^0{}_i$	periods during which the ith thermal generating unit has been on-line at the start of the scheduling period (h)
$v_{0,j}$	minimum storage volume of the reservoir pertaining to the jth hydro generating unit (Hm^3)
v_j^0	reservoir at the beginning of the scheduling period (Hm^3)
v_j^{Θ}	reservoir at the conclusion of the scheduling period (Hm^3)
$v_{n,j}$	maximum storage volume of the jth reservoir pertaining to the variable head n (Hm^3)

Variables

β	weighting factor in NBI method
$\beta_{n,i,t}$	binary variable which is equal to 1 when the nth block of cost curve pertaining to the ith thermal generating unit at time t is chosen
$\beta_{n,j,t}$	binary variable which is equal to 1, provided that variable head $n+1$ of the jth hydro generating unit at time t is chosen
$\delta_{n,i,t}$	generation of the nth block relating to the cost curve of the ith thermal generating unit at time t (MW)
Φ	payoff table
μ^r	aggregate membership function of the rth Pareto optimal solution
μ_n^r	individual membership function for the function n in the Pareto best solution r
$\psi_{n,j,t}$	the volume of the nth block of the reservoir pertaining to the jth hydro generating unit at time t (Hm^3)
Ω	feasible region