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Enhanced merit order and augmented Lagrange Hopfield network for hydrothermal scheduling

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Abstract

This paper proposes an enhanced merit order (EMO) and augmented Lagrange Hopfield network (ALHN) for solving hydrothermal scheduling (HTS) problem with pumped-storage units. EMO is a merit order enhanced by heuristic search based algorithms and the ALHN is a continuous Hopfield network with its energy function based on augmented Lagrangian function. EMO is efficient in unit scheduling, whereas ALHN can properly handle generation ramp rate limits, and time coupling constraints such as limited fuel, water discharge for hydro units, and water balance for pumped-storage units. The proposed method solves HTS problem by optimizing step by step of sub-problems in four phases. In the first phase, EMO is applied to solve only thermal unit commitment satisfying power balance, spinning reserve, limited fuel, and minimum up and down time constraints. In the second phase, the enhanced ALHN is used to solve economic dispatch (ED) and commit hydro units based on the obtained unit schedule from the first phase. In the third phase, the enhanced ALHN is applied to handle transmission constraint. In the last phase, the enhanced ALHN is used to commit pumped-storage units and solve final constrained ED. In each phase, heuristic search based algorithms are applied to repair the constraint violations and refine the obtained solution. The proposed EMO–ALHN is tested on a hydrothermal system with 17 thermal, 2 hydro, and 2 pumped-storage hydro units with a scheduling time horizon of 24 h. Test results indicate that the proposed method obtains less costs and faster computational times than those from augmented Hopfield neural network (AHN) and hybrid enhanced Lagrangian relaxation and quadratic programming (Hybrid LRQP) for two test cases.

Keywords: Augmented Lagrange Hopfield network; Merit order; Hydrothermal scheduling

1. Introduction

Hydrothermal scheduling (HTS) is generally used to minimize the total fuel cost of thermal units satisfying hydraulic and other unit and system constraints over a given scheduling time horizon. The optimal scheduling of a hydrothermal power system is more complicated than thermal unit commitment since it is basically a mixed integer non-linear programming problem involving non-linear objective function and a mixture of linear and non-linear constraints.

Short term HTS problem has been solved by several conventional methods such as dynamic programming (DP) [1], mixed integer programming (MIP) [2], network flow programming (NFP) [3], decomposition and coordination method [4]. The computational efforts in NFP will drastically increase when there exists some convex branches in the flow network. On the other hand, MIP requires linearization whereas the decomposition and coordination method may encounter difficulties when dealing with the operating limits and non-linearity of objective function and/or constraints. DP method appears to be the most popular among these methods. However, DP computational and dimensional requirements increase drastically with large-scale system planning horizon. Lagrange relaxation (LR) method has been widely used in HTS problems

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Nomenclature

b_g	consumed water rate of pumped-storage unit g (acre ft/MWh)
b_p	pumped water rate of pumped-storage unit p (arce ft/MWh)
D_{li}	sensitivity coefficient for power flow in line l with respect to power output of thermal unit i
D_{lh}	sensitivity coefficient for power flow in line l with respect to power output of hydro unit h
DR_i	ramp down rate of thermal unit i (MW/h)
DR_j	ramp down rate of fuel constrained unit j (MW/h)
E_j	target energy for fuel constrained unit j corresponding to Q_j (MWh)
ER^t	excessive spinning reserve at hour t (MW)
$F_i(P_i^t)$	quadratic fuel cost function of thermal unit i $F_i(P_i^t) = a_i + b_iP_i^t + c_i(P_i^t)^2$ (\$/h)
i	index of thermal units
j	index of fuel constrained units
N_f	number of fuel constrained units
N_l	total number of transmission lines
N_t	total number of thermal units
N_h	total number of hydro units
N_p	number of major load peaks over a scheduling time
N_{ps}	total number of pumped-storage hydro units
$P_{h,\max}$	maximum power generation of hydro unit h (MW)
$P_{h,\min}$	minimum power generation of hydro unit h (MW)
$P_{i,\max}$	maximum power generation of thermal unit i (MW)
$P_{i,\min}$	minimum power generation of thermal unit i (MW)
$P_{j,\max}$	maximum power generation of fuel constrained unit j (MW)
$P_{j,\min}$	minimum power generation of fuel constrained unit j (MW)
P_i^t	output power of thermal unit i at hour t (MW)
$P_{l,\max}$	power flow limit of transmission line l (MW)
P_l^t	power flow on transmission line l at hour t (MW)
$P_{p,\max}$	maximum power generation of pumped-storage hydro unit p operating as a pump (MW)
$P_{p,\min}$	minimum power generation of pumped-storage hydro unit p operating as a pump (MW)
P_D^t	system load demand at hour t (MW)
P_R^t	system spinning reserve at hour t (MW)
$q_g(P_g^t)$	consumed water function of pumped-storage hydro unit g operating as a generator (acre ft/h)
Q_h	total water discharge for hydro unit h (acre ft)
$q_h(P_h^t)$	consumed water function of hydro unit h (acre ft/h)
Q_j	total fuel supply for thermal unit j (Mcf)
$q_j(P_j^t)$	consumed fuel function of fuel constrained thermal unit j (Mcf/h)
$q_p(P_p^t)$	consumed water function of pumped-storage hydro unit p operating as a pump (acre ft/h)
R^t	spinning reserve of thermal system without fuel constrained units (MW)
SU_i^t	start up cost of thermal unit i at hour t (\$)
T	total number of hours over a scheduling time horizon
$T_{i,\mathrm{down}}$	minimum down time of thermal unit i (h)
$T_{i,\mathrm{off}}^t$	continuous off time of thermal unit i at hour t (h)
$T_{i,\mathrm{on}}^t$	continuous on time of thermal unit i at hour t (h)
$T_{i,\mathrm{up}}$	minimum up time of thermal unit i (h)
T_j	duration before and after each load peak hour for operation of fuel constrained unit j
$T_{j,\mathrm{up}}$	minimum up time of fuel constrained unit j (h)
$T_{j,\mathrm{rdn}}$	number of hours for fuel constrained unit j to decrease its power from $P_{j,\max}$ to $P_{j,\min}$ (h)
$T_{j,\mathrm{rup}}$	number of hours for fuel constrained unit j to increase its power from $P_{j,\min}$ to $P_{j,\max}$ (h)
$T_{j,\mathrm{opt}}$	optimal number of committed hours of fuel constrained unit j (h)
U_h^t	status of hydro unit h at hour t (on = 1; off = 0)
U_i^t	status of thermal unit i at hour t (on = 1; off = 0)
U_p^t	status of pumped-storage unit p operating as a pump at hour t (on = 1; off = 0)
UR_i	ramp up rate of thermal unit i (MW/h)
UR_j	ramp up rate of fuel constrained unit j (MW/h)
χ_i, δ_i, τ_i	start up coefficients of thermal unit i
ξ	cycle efficiency of pumped-storage hydro units
λ^t	lagrange multiplier for power balance at hour t (\$/MWh)
γ_j	pseudo fuel price of fuel constrained unit j (\$/Mcf)
η_h	pseudo fuel price of hydro unit h excluding pumped-storage units (\$/acre ft)
μ_l^t	pseudo transmission price of line l at hour t (\$/MWh)
φ	pseudo cost for pumped-storage units (\$/MW)
β_λ^t	penalty factor for power balance constraint
$\beta_{\gamma,j}$	penalty factor for fuel limitation constraint
$\beta_{\mu,l}^t$	penalty factor for transmission constraint
$\beta_{\eta,h}$	penalty factor for hydro discharge constraint
β_φ	penalty factor for water balance of pumped-storage hydro plants
Ω_f	set of fuel constrained units
Ω_g	set of pumped-storage units operated as generators
Ω_p	set of pumped-storage units operated as pumps