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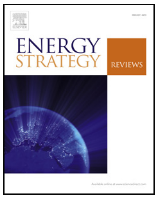

Fixed head short-term hydrothermal scheduling in presence of solar and wind power

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A B S T R A C T

A probabilistic short-term hydro-thermal-wind-photovoltaic scheduling based on point estimate method (PEM) is proposed in this article. To model the uncertainties associated with wind and solar power, point estimate method is used. The Weibull and Beta distributions are employed to handle the uncertain input variables. The mean generation cost of the system is optimized based on an optimization algorithm named crow search algorithm (CSA). Three test systems have been taken, the first test system contains only hydro and thermal plants, and rest of the two systems are based on wind and solar including hydro and thermal unit to investigate the effect of renewable energy sources in the selected test systems. Furthermore, underestimation and overestimation of available wind power has also been included in the problem. The simulation results show that when the penetration of renewable energy sources increases, the mean generation cost decreases. The results obtained by CSA have been compared with other well-known methods. Moreover, the accurate distribution of generation cost for the next day-ahead can be found out using Gram-Charlier series expansion.

1. Introduction

Being a large and complex network, power system has to deal with generation, transmission and distribution of power. The power system is expected to supply the changing load demand of the consumer at an economical way. Thus the importance of short-term hydrothermal scheduling (SHTS) problem has increased in recent years. The primary goal of SHTS problem is to minimize the generation cost of the thermal unit within a specific time interval by utilizing the available water of the hydro reservoir in an optimum manner. The reservoirs are basically connected in a cascaded way. The present SHTS problem has certain equality and inequality constraints which makes the problem complex and very interesting for power system engineers.

Nomenclature		$P_D(t)$	Total demand at time interval *t*.
Indices		$P_{loss}(t)$	Total transmission loss at time interval *t*.
i	Index of hydro power units.	*OEC(m,t)*	Overestimation cost of m^{th} wind unit at time interval *t*
j	Index of thermal power units.	*UEC (m,t)*	Under estimation cost of m^{th} wind unit at time interval *t*.
L	Index of solar power units.	C_{oe}, C_{ue}	Overestimation and under estimation cost coefficient
M	Index of wind power units.	*k*, *c*	Shape (dimensionless) and scale factor (*m*/*s*) of wind turbine
T	Index of time periods.	C_w	Direct cost coefficient of wind unit.
U	Index of upstream reservoir.	*v*	The current wind speed (*m*/*s*).
Sets		w_r	Rated power of wind turbine (*MW*).
N_h		v_r, v_{in}, v_{out}	

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	Total number of hydro unit.
N_t	Total number of thermal unit.
N_w	Total number of wind unit.
N_s	Total number of solar unit
TI	The total time interval.
Variables	
$D_h(i, t)$	Discharge of i^{th} hydro unit at time interval of t (m^3).
$H_p(i, t)$	Output of hydro power generation in MW at time interval *t*.
$I_h(i, t)$	Inflow rate of i^{th} hydro unit at a time interval of *t*.,
$S_p(l, t)$	Output of thermal power generation in MW at time interval *t*.
$T_p(j, t)$	Output of thermal power generation in MW at time interval *t*.
$V_h(i, t)$	Reservoir volume of i^{th} hydro unit at interval *t*.
$W_p(m, t)$	Output of wind power generation in MW at time interval *t*.
Constants	
$\alpha_j, \ \beta_j, \ \chi_j, \ \delta_j, \ \varepsilon_j$	Fuel cost coefficient of j^{th} thermal plant.
$J_{1i}, \ J_{2i}, \ J_{3i}, \ J_{4i}, \ J_{5i}, \ J_{6i}$	Hydro power output coefficient. Which relate discharge and volume with power output.
$T_p^{\min}(j), \ T_p^{\max}(j)$	Minimum and maximum power generation limit of j^{th} thermal unit.
$H_p^{\min}(i), \ H_p^{\max}(i)$	Minimum and maximum power generation limit of i^{th} hydro unit.
$D_h^{\min}(i), \ D_h^{\max}(i)$	Minimum and maximum discharge limit of i^{th} hydro reservoir (m^3).
$V_h^{\min}(i), \ V_h^{\max}(i)$	Minimum and maximum reservoir storage volume limit of i^{th} hydro reservoir.
τ_u	Water transport delay.
$R_u(i)$	Number of upstream reservoirs immediately above i^{th} hydro unit.
$V_h^{begin}(i), \ V_h^{end}(i)$	Initial and final storage volume of i^{th} hydro reservoir.
	The rated, cut-in and cut-out speed of wind turbine (m/s).
ζ	The amount of solar irradiance in $\mathrm{kw/m^2}$
bid	Bid rate related to solar power cost.
$\omega, \ \psi$	Beta PDF parameter.
$S_{rad}(t)$	Solar radiation (W/m^2) of PV at time interval *t*.
$S_{rad,stc}$	Solar radiation for standard test condition (stc).
$S_{p,stc}$	Solar power for standard test condition (stc).
γ	Power temperature coefficient.
T_{cell}	Cell temperature $(°C)$ of PV
$T_{cell,stc}$	Reference cell temperature $(°C)$ of PV.
$N_{sc}, \ N_{pc}$	Number of series and parallel cells of PV.
T_{amb}	Environmental temperature $(°C)$
$NOCT$	Normal operating cell temperature $(°C)$

To solve SHTS problem, different approaches have been taken by the researchers so far. At the beginning some classical optimization techniques like Linear programming (LP) [1], Lagrange relaxation (LR) [2], mixed integer programming (MIP) [3], Gradient search (GS) [4], Dynamic programming (DP) [5], etc. were used. But all these methods have their own advantages and disadvantages. Later on, evolutionary algorithms have been extensively used and became popular due to their flexibility and robustness to find the optimal solution. Many evolutionary algorithms already applied to solve the SHTS problem are: simulated annealing (SA) [6,7], Evolutionary programming (EP) [8], Differential Evolution (DE) [9], Genetic Algorithm (GA) [10], Particle swarm optimization (PSO) [11] and some other PSO based algorithms [12,13]. Later on, some other population based optimization techniques like Artificial immune system (AIS) [14], real coded chemical reaction based optimization (RCCRO) [15]; Teaching learning based optimization (TLBO) [16], Cuckoo search algorithm (CSA) [17], Disruption based gravitational search algorithm (DGSA) [18] and Symbiotic organisms search (SOS) algorithm [19] have been successfully implemented to solve SHTS problem. In 2017 Esmaeily et al. [20] proposed MILP to solve hydro-thermal self-scheduling problem considering price uncertainty and forced outage rate to maximize the expected profit. An improved harmony search (IHS) optimization algorithm has been successfully applied by Nazari-Heris et al. [21] in 2018 to solve short-term hydrothermal scheduling problem. Two test systems have been considered to justify the performance of IHS algorithm. Feng et al. [22] proposed multi-objective quantum-behaved particle swarm optimization (MOQPSO) algorithm to solve the HTS problem. In this article, the authors have taken a multi-objective problem to minimize cost as well as emission. A real-coded genetic algorithm based on improved Mühlenbein mutation (RCGA-IMM) algorithm has been successfully