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Short-term peak shaving operation for multiple power grids with pumped storage power plants

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ABSTRACT

The East China Power Grid (ECPG) is the biggest regional power grid in China. It has the biggest installed capacity of pumped storage power plants (PSPPs) and is responsible to coordinate the operation of its five provincial power grids. A recent challenge of coordinating operations is using PSPPs to absorb surplus energy during off-peak periods and generate power during peak periods. Differing from the traditional operations of single power grids, however, the PSPPs are required to respond to load demands from multiple provincial power grids simultaneously. This paper develops a three-step hybrid algorithm for the day-ahead quarter-hourly schedules of PSPPs to meet load demands of multiple provincial power grids. A normalization method is first proposed to reconstruct a total load curve to deal with the load differences of multiple provincial power grids, and to reflect the effect of specified electricity contract ratio on multiple provincial power grids. Secondly, a heuristic search method is presented to determine the generating and pumping powers of PSPP. Thirdly, a combination optimization method is used to allocate the determined generating and pumping powers among multiple provincial power grids to smooth the individual remaining load curve for their thermal systems. Two case studies with greatly different load demands are used to test the proposed algorithm. The simulation results show that the presented method can effectively achieve the goal of shaving the peak load and filling the off-peak load for multiple provincial power grids.

Introduction

China's electricity demand has a huge expansion during the past three decades with its growing economy. The East China Power Grid (ECPG), which is the biggest regional power grid in China, consists of five provincial power grids in eastern China, in Fig. 1. Its maximum electricity load exceeded 184.5 GW in 2012, about 26 times larger than in 1982. Its maximum load difference between peak and off-peak has also largely increased by about 4.59 times, from 11.96 GW in 2002 to 54.86 GW in 2012. Fig. 2 shows the total load demand of ECPG, and individual load demands of multiple provincial power grids on December 24, 2012. The maximum load difference of ECPG between peak and off-peak has reached 54.86 GW (29.7% of maximum electricity load). This expansion of load demands brings significant challenges to the ECPG, since over 84.8% of its total installed capacity (about 178.9 GW) is thermal power that has low effective capacity of regulating peak loads.

Hydropower plants are unevenly distributed among multiple provincial power grids in ECPG. From the provincial energy structures in Fig. 3, the Fujian Power Grid has 32.4% of hydropower and little pressure on peak power demand, while the other four provincial power grids face severe power shortages for peak demand. The pressing demand for peak power resulted in a rapid establishment of pumped storage power plants (PSPPs) [1,2] in the ECPG. The PSPPs owned by the ECPG are the biggest in China [3], with a total installed capacity of 7.12 GW (35.6% of nation's total PSPPs capacity). Table 1 shows the details of PSPPs in the ECPG. Among the established PSPPs, the four bigger plants including Tianhuangping, Xiangshuijian, Langyashan and Tongbai are directly operated by the dispatching center of the ECPG to absorb surplus energy from four provincial power grids (SHPG, JSPG, ZJPG and AHPG) and then provide peak power for these power grids. The other PSPPs are operated by different provincial power grids for meeting their local load demands respectively. This paper focuses on the former one of operating the four bigger PSPPs. A system-wide practical problem is how to determine the day-ahead quarter-hourly schedules for these PSPPs to coordinate extremely different peak and off-peak load demands among multiple provincial power grids.

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Nomenclature

A. Acronyms

ECPG	East China Power Grid
PSPPs	pumped storage power plants
PSPP	a pumped storage power plant
SHPG	Shanghai Power Grid
JSPG	Jiangsu Power Grid
ZJPG	Zhejiang Power Grid
AHPG	Anhui Power Grid
FJPG	Fujian Power Grid

B. Indices

k	PSPP or upper reservoir index
g	provincial power grid index
t	time period index
j	candidate solution index
n_1	iteration index
n_2	iteration index
K	number of PSPPs
G	number of provincial power grids
T	scheduling horizon
J	number of candidate solutions

C. Parameters and constants

Δt	time period duration (=0.25 h).
$\overline{q}_{k,t}^{output}$	maximum water discharge limits (m^3/s)
$\underline{q}_{k,t}^{output}$	minimum water discharge limits (m^3/s)
$\overline{q}_{k,t}^{input}$	maximum pumping flow limits (m^3/s)
$\underline{q}_{k,t}^{input}$	minimum pumping flow limits (m^3/s)
$\overline{V}_{k,t}^{up}$	maximum storage of upper reservoir (m^3)
$\underline{V}_{k,t}^{up}$	minimum storage of upper reservoir (m^3)
$\overline{V}_{k,t}^{low}$	maximum storage of lower reservoir (m^3)
$\underline{V}_{k,t}^{low}$	minimum storage of lower reservoir (m^3)
$V_{k,T}^{\prime up}$	final storage target of upper reservoir (m^3)
$\overline{N}_{k,t}^{output}$	maximum generating power (MW)
$\underline{N}_{k,t}^{output}$	minimum generating power (MW)
$\overline{N}_{k,t}^{input}$	maximum pumping power (MW)
$\underline{N}_{k,t}^{input}$	minimum pumping power (MW)
ΔN_k^{output}	maximum ramping capacity in generating model (MW)
ΔN_k^{input}	maximum ramping capacity in pumping model (MW)
$E_k^{\prime output}$	specified total energy generation target (MW h)
$R_{k,g}$	specified electricity contract ratio
tg_k	minimum duration periods of operation
ts_k	minimum duration periods of shutdown
T_r	extreme point duration periods
w_g^{α}	weight coefficient

D. Variables

$L_{g,t}$	original load demand (MW)
$C_{g,t}$	remaining load demand (MW)
$\overline{C}_g$	mean of the remaining load (MW)
C_g^{max}	maximum remaining load (MW)
C_g^{min}	maximum remaining load (MW)
$C_{k,t}^{total}$	total remaining load (MW)
$N_{k,t}$	generating power (positive values, MW)
$N_{k,t}$	pumping power (negative values, MW)
$N_{k,t}^{g}$	supply power for gird (positive values, MW)
$N_{k,t}^{g}$	absorb power from grid (negative values, MW)
D_g	variance of the remaining load
$D_{g,j}$	candidate solution
D_g^{max}	maximum candidate solutions
D_g^{min}	minimum candidate solutions
W_g^{a}	weight coefficient
$V_{k,t}^{up}$	water storage of upper reservoir (m^3)
$V_{k,t}^{low}$	water storage of lower reservoir (m^3)
$q_{k,t}$	water discharge (positive values, m^3/s)
$q_{k,t}$	pumping flow (negative values, m^3/s)
$Z_{k,t}^{up}$	water level of upper reservoir (m)
$Z_{k,t}^{low}$	water level of lower reservoir (m)
$H_k^{t,t+1}$	average gross head
$\overline{\tau}_{k,t}$	maximum extreme point duration periods
$\underline{\tau}_{k,t}$	minimum extreme point duration periods
$f_{output}(\bullet)$	generating power function
$f_{input}(\bullet)$	pumping power function
$f_{z-v}^{up}(\bullet)$	water level and storage function of upper reservoir
$f_{z-v}^{low}(\bullet)$	water level and storage function of lower reservoir

Different from the traditional operations of PSPPs for a single power grid [4–7], the PSPPs in ECPG are usually required to shave the peak load and fill the off-peak load (Fig. 4) for multiple provincial power grids according to multilateral electricity contracts. It is difficult to coordinate generating power and pumping power of PSPPs to respond promptly to different load demands because of the strong electrical coupling, inconsistent load demand with largely varying magnitude and peak and off-peak periods among multiple provincial power grids. Besides, the traditional reservoir and hydropower plant constraints and multilateral electricity contracts are coupled across the entire scheduling horizon, which make it more difficult to find rational and efficient operational schedules for PSPPs.

Optimization of PSPP scheduling is an important area that has attracted many researches. Various methods have been developed to resolve the problem, including Linear Programming (LP) [6], Mixed Integer Programming (MIP) [8,9], Dynamic Programming (DP) [10–12], Lagrangian Relaxation algorithm (LR) [9], Artificial intelligence algorithm [13–15], practical operation strategies [16–19] and commercial software [20,21]. However, these methods have some limits. For instance, LP, MIP and commercial software may not guarantee the accuracy of optimized results due to the linearization or piecewise linearization of nonlinear objective functions and constraints. DP is not an efficient method for solving short-term operation of multiple PSPPs among multiple power grids because of the acknowledged curse of dimensionality [22,23]. A similar study has confirmed the inefficiency of DP [10] that uses DP method to obtain the optimal scheduling of one PSPP in combination with several interconnected power systems. LR is not applicable to deal with dynamic transition among operating states (generating, pumping and idle) and optimizing multipliers, and is not an effective method for our problem. Furthermore, many