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Multi-objective operation optimization and evaluation of large-scale NG distributed energy system driven by gas-steam combined cycle in China

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ABSTRACT

Many pilot projects of large-scale distributed energy resources (DER) system have been constructed recent years in China and operation strategies make a great impact on their benefits and further development. This paper presents a multi-objective (joint) optimization model for the large-scale DER system of Guangzhou Higher Education Mega Center to obtain the optimal operation strategies under different daily periods: peak periods, flat periods, and valley periods. The prime mover used in this investigation is a gas-steam combined cycle based on combined gas turbines and steam turbines, and the DER system is evaluated under three different operation optimization modes: joint optimization mode of variable operational cost (VOC) and primary energy rate (PER), VOC optimization mode, and PER optimization mode. The primary energy consumption (PEC), PER, operational costs, and investment benefits of the DER system under different operation strategies of above three optimization modes are evaluated comparing with the buildings using conventional technologies. Results indicate that the VOC optimization mode provides the best combined cooling, heating, and power (CCHP) performance during flat periods by yielding the lowest PEC (133.78 kton/year) and operational cost (million $ 35.98/year), and the joint optimization mode shows the best performance during peak periods by producing the lowest PEC (80.42 kton/year) and similar low operational costs (million $ 21.74/year) to VOC optimization mode (million $ 20.89/year).

1. Introduction

DER system refers to electric power generation system that is directly connected to medium voltage (MV) or low voltage (LV) distribution systems, rather than to the bulk power transmission systems [1]. DER is one of the modern energy supply modes, which could directly provide energy supply in the load centers, and realizes efficient utilization of various clean energy resources. The primary energy resources for DER are various, including natural gas (NG) energy sources, solar energy sources, wind energy sources, geothermal energy sources, biomass energy sources, etc. DER can be applied to many fields for various buildings, such as base load generation, emergency backup and peak/load shaving for industrial parks, university towns, airports, residential buildings, commercial buildings, and office buildings, etc. Most of DER systems mentioned above use NG as primary energy sources and are configured according to their energy demand characteristics. Many strong advantages of DER have been showed during its application, such as higher energy efficiencies, environmental conservation, higher reliability, lower cost and higher flexibility, etc [2].

Considering above strong advantages, DER, especially the distributed NG, has obtained great concern recent years in China. To encourage the development and utilization of distributed NG, the policy "*Guidance for NG distributed energy resources development*" was formulated by National Development and Reform Commission and National Energy Administration in 2011. According to the policy, NG DER is defined as the distributed generation with NG as the primary energy source, and realizes the energy cascade utilization by combined cooling, heating and power, which many times boosts comprehensive energy utilization efficiencies to up to 70%. That is, NG distributed energy system is usually the CCHP system using waste heat from on-site electricity generation to meet the thermal demand of the facility. By the end of 2012, multiple pilot projects of NG distributed energy systems have been put into use in many places of China, such as Guangzhou Higher Education Mega Center, PVG, Shanghai Universal International Financial Center,

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Nomenclature

Variables

E	electricity
F	fuel input
Q_{fg}	fuel gas yielded by gas turbines
Q_{efg}	exhausted fuel gas from HRSG
Q_{HPs}	high-pressure steam yielded by HRSG
Q_h	heat energy
$Q_{ES,AC}$	heat provided by extracted steam of steam turbines to absorption chillers
$Q_{ES,HE}$	heat provided by extracted steam of steam turbines to heat exchanger for hot water
$Q_{HW,HE}$	heat recovered from heat medium water to heat exchanger for hot water
$Q_{HW,AC}$	heat recovered from heat medium water to absorption chillers for cooling
Q_c	cooling energy
PLR	part load ratio of gas turbine
E_r	rated electricity generation under full load condition
E_{el}^{conv}	electricity required by buildings under conventional technology
e	the station service power consumption rate of CCHP system
PEC_e	the primary energy conversion factors for electricity
PEC_{ng}	the primary energy conversion factors for natural gas
PEC_h	the primary energy conversion factor for heating from thermal power plant
p	price of energy
Cost	operational cost
i	discount rate
n	the total operation years of CCHP system
I_0	initial investments of CCHP system
P_j	the dynamic payback period of CCHP system
t	the tth hour or the tth time period
k	the kth period, $k = 1$ means the valley period; $k = 2$ means the flat period; $k = 3$ means the peak period
m	the mth month, $m = 1, 2, \ldots, 12$
T_k	the duration hours or time of kth period
HV	heat value of energy
α	weight coefficient

Greek

η	efficiency
δ	proportion of extracted steam from steam turbine to the available steam extraction

Subscripts

PE	primary energy
grid	grid
load	energy load required by the buildings
ng	natural gas
HW	hot medium water
ES	extracted steam
fg	fuel gas
efg	extracted fuel gas
HPs	high-pressure steam
g	total generation
el	electricity
EC	electric chillers
buy	buy from the grid
export	export to the grid
loss	loss
max	maximum
min	minimum
h	heat load
oth	other
j	operation year

Superscripts

conv	conventional technology

Acronyms

AC	absorption chillers
CC	compression electrical chillers
CCHP	combined cooling heating and power
CHP	combined heating and power
COP	coefficient of performance
CS	cost savings
CSR	cost saving ratio
CSS	conventional separated system
DER	distributed energy resources
DES	distributed energy system
DPP	dynamic investment payback period
ESR	energy saving ratio
FEL	following the electric load
FTL	following the thermal load
GHEMC	Guangzhou Higher Education Mega Center
GT	gas turbines
HE	heat exchanger
HETS	hybrid electric-thermal load strategy
HRSG	heat recover steam generator
KW	kilowatt
LV	low voltage
MINLP	mixed-integer non-linear programming
MOLP	multi-objective linear programming
MV	medium voltage
MW	megawatt
NG	natural gas
NPV	Net Present Value
PEC	primary energy consumption
PER	primary energy rate
ST	steam turbines
TOC	total operational costs
VOC	variable operational cost

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The sizes and applications of DES vary to a considerable degree, ranging in size from a few kilowatts (KW) to megawatts (MW) of power production, with applications to residential, commercial, industrial, or large-scale DES [3]. In general, there are usually two basic operation strategies for DES or CCHP systems: following the electric load (FEL) and following the thermal load (FTL). In the case of FEL operation strategy, the prime mover is loaded according to the electric demand of the facility and the waste heat from this loading is recovered to satisfy the thermal load of the facility. If the recovered thermal energy is not enough to handle the thermal load (cooling or heating) of the facility, additional heat has to be provided by the auxiliary boiler of the CCHP system. For the FTL strategy, the prime mover is loaded such that the recovered waste heat will be adequate to supply the facility with the necessary thermal energy to satisfy the heating and cooling requirements. For this strategy the amount of electricity produced may be insufficient or