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A two-stage optimal planning and design method for combined cooling, heat and power microgrid system

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ABSTRACT

In this paper, a two-stage optimal planning and design method for combined cooling, heat and power (CCHP) microgrid system was presented. The optimal objective was to simultaneously minimize the total net present cost and carbon dioxide emission in life circle. On the first stage, multi-objective genetic algorithm based on non-dominated sorting genetic algorithm-II (NSGA-II) was applied to solve the optimal design problem including the optimization of equipment type and capacity. On the second stage, mixed-integer linear programming (MILP) algorithm was used to solve the optimal dispatch problem. The approach was applied to a typical CCHP microgrid system in a hospital as a case study, and the effectiveness of the proposed method was verified.

1. Introduction

Combined cooling, heat and power (CCHP) microgrid system is a small power system, which consists of many distributed units, such as power generation unit, energy storage unit. Among the distributed units, cogeneration unit is the key equipment, which generates electricity and heat simultaneously. With the gradual depletion of the traditional fossil fuels and the increasing attention to environmental issues, the CCHP microgrid system is regarded as an effective organization form of distributed energy supply units, with low consumption highly-efficient utilization of primary energy, low emissions, and high reliability [1–4]. Hence it is widely recognized as an alternative method to solve the problems of the energy and environment [5–7].

How to use the CCHP equipments and renewable energy to build the CCHP microgrid system is receiving a great deal of attention [8,9]. As is known to all, the reasonable planning is an important premise and guarantee for stable and efficient operation of CCHP microgrid system. A lot of works have been carried out on the related researches, which can be generally divided into the following three aspects: the assessment indicators and methods, the operation strategy and the optimal planning of CCHP microgrid system. With regard to assessment indicators and methods, the performance indices of economy, reliability, emission and energy utilization efficiency etc. are the key factors to analyze the performance of CCHP microgrid system. Viewing from the point of the total net present cost (NPC) in life circle, internal rate of return and dynamic payback period, Smith et al. [10] make a financial analysis for a CCHP microgrid system. Wang et al. [11] proposed a comprehensive evaluation system for CCHP system, including the annual primary energy saving (PSV), annual total cost saving (ATCS) and carbon dioxide emission reduction, which was used to assess the performance of CCHP system in different climate regions in China. The annual operation cost, primary energy consumption and carbon dioxide emissions are taken as the comprehensive evaluation indicators, and a comparative analysis is performed according to the different operation strategies of CCHP system [12,13]. For the operation strategy of CCHP microgrid system, there are two basic methods, namely, following the thermal load (FTL) and following the electric load (FEL). They were also referred to as the thermal demand management (TDM) and the electric demand management (EDM) [14], or heat tracking (HT) and electricity tracking (ET) [15] as well. When operating at FTL mode, the cogeneration system put the priority on heat production; if the cogeneration system could not meet the electrical load demand, the shortfall would be purchased from the grid. When operating at FEL mode, the cogeneration system meets electric demand first; if heat generated by the cogeneration system could not meet heat load demand, the boiler would supply additional heat. However, both FEL and FTL strategies will inherently waste energy [16]. Based on FTL and FEL, the strategy of following hybrid electric-thermal load (FHL)

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Nomenclature

AC	absorption chiller
B	boiler
C	cost
CCHP	combined cooling heating and power
CDE	carbon dioxide emission
CL	cooling load
COP	coefficient of performance
CRF	the capital recovery factor
DC	double duty chiller unit
DT	distribution transformer
EC	electric chiller
EL	electric load
ES	electrical storage
HL	heat load
HPR	heat to power ratio
ICE	internal-combustion engine
ISAC	ice storage air conditioning system
IST	ice-storage tank
MILP	mixed integer linear programming
MT	micro turbine
NPC	net present cost
NSGA	non-dominated sorting genetic algorithm
PGU	power generation unit
PV	photovoltaic
SOC	state of charge
SP	separate production
TS	thermal storage
W	capacity
X/Y	binary variable
l	the number of years
r	the interest rate

Greek symbols

α	heat to power ratio
β	emission conversion factor
μ	binary variable
γ	charging and discharging ratios
η	efficiency

Subscripts

d	typical day
h	hour
k	*k*th equipment
m	month
t	time period

Superscripts

E	electricity
F	fuel
I	initial investment costs
If	fixed initial investment cost
Iv	variable initial investment cost
M	maintenance costs
Mv	variable maintenance cost
Mf	fixed maintenance cost
N	rating power or capacity
O	operating costs
a	annual
c	charge
cool	refrigeration mode
d	discharge
dc	demand charge
df	demand fees
fc	the basic per-unit capacity cost
ff	fixed fees
gas	natural gas
grid	grid
ice	ice-making mode
in	the input power of an equipment
out	the output power of an equipment
vf	volumetric fees

was proposed [12,17], which can switch between the two basic ones according to electrical, thermal load and the performance of prime mover. This strategy addressed the issue of waste energy in FTL and FEL strategy, and represented higher economic and environmental performance. However, the strategy is still a static one which searches the optimal solution in each separated time period, without taking the relationships among different periods into account. Shaneb et al. [18], presented an optimal online operation strategy using linear programming algorithm, which can significantly reduce energy consumption and operating costs of the system, but the strategy was only applied to the combined heat and power (CHP) system. Zhang et al. [19] developed a dynamic optimal scheduling model with two optimal objectives to maximum the distributed energy resources energy output and to minimum system's daily operating cost. And according to the day-ahead cooling, thermal and electrical load data, the literature used mixed-integer nonlinear programming algorithm (MINLP) to solve the dispatching problem, which can more accurately reflect the real picture of the system. However, the calculation speed and accuracy are limited by the chosen tool. For the optimal planning of CCHP microgrid system, Zhang and Karady [20] pointed out that the equipment style and capacity should be selected according to their characteristics, efficiency, initial cost as well as load demand conditions. In general, the problem is a hybrid optimal planning problem including discrete and continuous variables, which can be well solved by intelligent algorithm. Taking the same assessment indicators as those in Ref. [11], Wang et al. [5] employed genetic algorithms to optimize the capacity for a CCHP system, which was composed of power generation unit (PGU), absorption chiller, electrical chiller and boiler. However, only the capacity of PGU and the ratio of electric cooling to cooling load were optimized in this paper. Adopting the similar optimization goals, Wang et al. [21] chose the capacity of PGU and heat storage tank, the on–off coefficient of PGU and the ratio of electric cooling to cool load as optimal variables, and utilized particle swarm algorithm to solve the planning problem. In Refs. [5,21], they transformed multi-objective optimal problem into single objective optimal problem by weighted value, which can be called weighted-sum method. Considering CCHP microgrid system with a variety of distributed units and storage units, a mixed integer linear programming (MILP) is constructed model to solve the united optimization problem of planning and operation strategy, which integrates synthesis optimization (to determine the components appear in a system), design optimization (to determine the capacity of each equipment) and operation optimization together (to determine the operating schedule) [22,23]. However, this method can only solve single-objective optimal problems.

Researches show that CCHP system performance is largely dependent on its design (including equipment type and capacity) and operation strategy [24]. However, most of those optimal planning and design studies failed to take all of the factors relative to the performance of system into account, including the type and