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Optimal coordinated energy dispatch of a multi-energy microgrid in grid-connected and islanded modes

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ABSTRACT

This paper proposes a system-wide optimal coordinated energy dispatch method for a multi-energy microgrid in both the grid-connected and islanded modes. The studied microgrid consists of multiple energy carriers covering the controllable generation units (fuel cell, electric boiler, combined cooling, heat and power plant and electric chiller), uncontrollable generation units (wind turbine and photovoltaic cell) and energy storage devices (battery storage, heat storage tank and ice storage tank). The proposed energy dispatch method aims to minimize the microgrid net operating cost and enhance the dispatch flexibility in supplying power, heat and cooling in the day-ahead energy market. For both the grid-connected and islanded microgrid, their dispatch models are formulated as the mixed-integer linear programming problems, which can be efficiently solved by the commercial solvers. Comprehensive case studies are performed to evaluate the effectiveness of the proposed method and then compared with the traditional dispatch methods which supply power and heat/cooling energies separately. Simulation results demonstrate that the proposed method can achieve much higher operating efficiency.

1. Introduction

Multi-energy systems aim to integrate diverse energy carriers such as electricity, heat and cooling, to achieve higher energy utilization efficiency [1]. In practice, the multiple energies can be simultaneously generated by highly efficient co- or tri-generation units such as the combined cooling, heat and power (CCHP) plant [2,3]. Once deployed in the distribution network, the CCHP plant, energy storage and the renewable energy-based distributed generation (DG) units such as solar and wind power can form a multi-energy microgrid [2–4]. Therefore, one key research problem is to optimally dispatch multi-energy related units for the maximum operating efficiency.

In the literature about the multi-energy integration, most of the research works focus on the operation at the individual CCHP plants level, which can generally fall into two strategies, *i.e.*, following power load (FPL) and following heat load (FHL) strategy [5–10]. Fang et al. [5] worked on the FPL/FHL switching strategies to enhance the integrated performance of energy consumption, operating cost and CO_2 emissions of the CCHP plant. Similarly, to minimize the excess power or heat energy produced by the CCHP plant, Smith et al. [6] compared the FPL and FHL with a hybrid strategy which either followed FPL or FHL strategy. In [7] and [8], operational strategies for CCHP plant were designed for different operational conditions and corresponding evaluation criteria. With a ground source heat pump, Kang et al. [9] configured a CCHP-organic Rankine cycle system and analyzed its performance in the cost savings, gas emission reduction, and system efficiency improvement. In [10], matrix modelling approach was introduced to optimize the input and output power of CCHP plant as well as its capacity. Although many research works have been done on the operation of the single CCHP plant, its coordination with other DGs to supply multiple energies at a system level (*e.g.*, microgrid) was not systematically studied.

At the microgrid level, most of the current research works focus only on the operation of single-energy microgrids [11–13], which do not integrate multiple energies. Further, the research works on the coordination of the CCHP plant with other DGs in supplying multiple energies are mainly for the grid-connected microgrids [14,15]. Ma et al. [16] investigated the coordination of the CCHP plant and photovoltaic prosumers to minimize the operating cost in a grid-connected microgrid. In [17], the robust optimization method was employed to coordinate the CCHP plant with DGs of uncertain outputs to handle the intermittency. Wang et al. [18] proposed an integrated multi-objective dispatch method for the microgrid to minimize its net operating cost and gas emissions. In [19], an optimization method for the operation and design of microgrid with power and heat demands was proposed considering the uncertainty of renewable energies. In our recent work [20], the dynamic dispatch method for a grid-connected multi-energy microgrid considering the opportunity profit by the electrical energy

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Nomenclature

Sets and indices

t set of dispatch time, running from 1 to N
j set of CG, running from 1 to N_{CG}
k set of the blocks, running from 1 to N_L
m set of the units, including WT, PV, MT, FC, EB, EC and ES, running for 1 to N_U

Variables and parameters

η_{MT}^t/η_{FC}^t electrical efficiency of MT/FC
P_{MT}^t/P_{FC}^t power outputs of MT/FC
Q_{MTH}^t/Q_{MTC}^t heat/cooling outputs of MT
η_H/η_C heat recovery ratio of the heat recovery unit/absorption chiller
COP_H/COP_C coefficient of performance of heat recovery unit/absorption chiller
η_L heat loss ratio of MT
E_{ES}^t energy stored in ES
P_{ESC}^t/P_{ESD}^t charging/discharging power of ES
τ_{ES} decay rate of ES
η_{ESC}/η_{ESD} charging/discharging rates of ES
Q_{EB}^t/Q_{EC}^t heat/cooling outputs of EB/EC
P_{EB}^t/P_{EC}^t power inputs of EB/EC
COP_{EB}/COP_{EC} heat/cooling coefficient of performance of EB/EC
F_G/F_S net operating cost of the grid-connected/islanded microgrid
C_{CP} capital cost
$C_{CP,m}/n_m$ initial investment cost/life span of unit m
l annual interest rate
C_F^t/C_{OM}^t fuel/maintenance cost
C_{EX}^t/C_{PH}^t power exchange/energy deviation cost
C_{ST}^t/C_{SD}^t start-up/shut-down cost
C_{HC}^t/C_{SHC}^t revenue of supplying heat/cooling in grid-connected/islanded microgrid
$C_{F,FC}^t/C_{F,MT}^t$ fuel cost of FC/MT
c_G/L_{NG} unit price/lower heating value of natural gas
P_{WT}^t/P_{PV}^t power outputs of WT/PV
K_{WT}^{om}/K_{PV}^{om} unit maintenance cost of WT/PV
$K_{EC}^{om}/K_{EB}^{om}/K_{MT}^{om}$ unit maintenance cost of EC/EB/MT
K_{FC}^{om}/K_{ES}^{om} unit maintenance cost of FC/ES
$C_{ST,j}^U/C_{SD,j}^D$ unit start-up/shut-down cost of unit j
P_B^t/P_S^t purchasing/selling power of microgrid
c_B^t/c_S^t unit power purchasing/selling price of microgrid
C_H^t/C_C^t revenue of supplying heat/cooling in grid-connected microgrid
c_H/c_C unit price of supplying heat/cooling to customers
P_{BSC}^t/P_{BSD}^t charging/discharging power of BS
P_{ISTC}^t/P_{ISTD}^t absorbing/releasing power of IST
P_{HSTC}^t/P_{HSTD}^t absorbing/releasing power of HST
Q_H^t/Q_C^t heat/cooling demands of microgrid
P_L^t power demands of microgrid
U_j^t binary status of unit j, $U_j^t = 1$ is on, 0 is off
$P_{CG,j}^t$ power of controllable unit j
$P_{CG,j}^{\min}/P_{CG,j}^{\max}$ minimum/maximum power of unit j
$R_{CG,j}^{up}/R_{CG,j}^{down}$ maximum ramp up/down rate of unit j
$P_B^{\max}/P_S^{\max}$ maximum purchasing/selling power of microgrid
γ_B^t/γ_S^t binary state variables with $\gamma_B^t = 1/\gamma_S^t = 1$, microgrid purchases/sells power
$P_{ESC}^{\max}/P_{ESD}^{\max}$ maximum charging/discharging power of ES
$\gamma_{ESC}^t/\gamma_{ESD}^t$ binary state variables with $\gamma_{ESC}^t = 1/\gamma_{ESD}^t = 1$, ES is charging/discharging
$\xi_{ES}^{\min}/\xi_{ES}^{\max}$ minimum/maximum state of charge of ES
Cap_{ES} capacity of ES
$c_{TE}/c_{IE}/c_{DE}$ unit cost for heat/cooling/power surplus
$c_{TS}/c_{IS}/c_{DS}$ unit cost for heat/cooling/power shortage
$Q_{TS}^t/Q_{IS}^t/P_{DS}^t$ heat/cooling/power shortage
$Q_{TE}^t/Q_{IE}^t/P_{DE}^t$ heat/cooling/power surplus
C_{SH}^t/C_{SC}^t revenue of supplying heat/cooling in islanded microgrid
$\gamma_{TS}^t/\gamma_{IS}^t/\gamma_{DS}^t$ binary indicators of heat/cooling/power shortage, 1 means that there is energy shortage
$\gamma_{TE}^t/\gamma_{IE}^t/\gamma_{DE}^t$ binary indicators of the heat/cooling/power surplus,1 means that there is energy surplus
α_k/β_k slope/intercept of linear function in block k
P_k starting point of kth block
P_1/P_{N+1} minimum/maximum power outputs of N_L blocks
Δt unit dispatch interval, 1 h
B_k^t binary state of block k
P_k^t general power output of MT or FC
$C_{U,FC}^t/C_{U,PG}^t$ unit power generation cost of FC/MT for only power generation
$C_{U,S}^t/C_{U,W}^t$ unit power generation cost of MT in summer/winter

storage was studied to increase the system operating efficiency.

Much work has been done on the operation of grid-connected microgrids in the literature, but very few research works consider the multi-energy dispatch of the islanded operating modes. Besides, the existing related works on the dispatch of islanded microgrids still focus on its single-energy dispatch only, *i.e.*, the power dispatch of the islanded microgrids [11,12,21–23]. In practice, the multi-energy management of the islanded microgrids is important especially for some remote areas like the Semakau Island microgrid in Singapore [4]. Without the grid as the backup, the operation objective of the islanded microgrids is rather different from the grid-connected ones. The research work in [24] is one of the few studies which proposed a multi-objective optimization method for the minimization of the fuel cost and gas emission.

It can be observed that for the operation of individual CCHP plant, all the above works adopt the FPL/FHL or hybrid of the two strategies; while at the system level, CCHP plant typically operates under the FHL strategy in grid-connected microgrids since the power imbalance can be compensated by the grid, for the islanded microgrids, the FPL strategy for CCHP plant is preferred in that the power system requires a precise power balance all the time but the imbalance of the heat/cooling energy for short periods is acceptable [14]. However, under the above strategies, power and heat/cooling outputs of the CCHP plant are highly coupled and dependent on one another, which makes the microgrid operation not flexible enough and the potentials of CCHP plant in the system cost saving are not fulfilled.

Moreover, given the nonlinear nature of the dispatch problem, the solution methods are mostly the evolutionary algorithms like the Genetic Algorithm or Particle Swarm Optimization [12,14,16–18,21,24]. However, these algorithms are computationally demanding, especially when the problem dimension is high. Further, they often suffer from issues such as the inconsistent solutions and difficult to rigorously converge. Since the new competitive environment in the power system requires more accurate and efficient tools to support decisions for the resource dispatch, more efficient solution process and quality are needed [25].

This paper studies on a comprehensive multi-energy microgrid which consists of a CCHP plant, a battery storage (BS), an electric chiller (EC), a heat storage tank (HST), a wind turbine (WT), a photovoltaic cell (PV), an ice storage tank (IST), an electric boiler (EB) and a fuel cell (FC). To achieve higher dispatch flexibility and operating efficiency, the system-wide optimal coordinated dispatch models for microgrid under both grid-connected and islanded modes are proposed. In the models, the HST and IST are utilized to decouple the inflexible