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Development of multi-supply-multi-demand control strategy for combined cooling, heating and power system primed with solid oxide fuel cell-gas turbine

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ABSTRACT

Combined cooling, heating and power (CCHP) system with the prime mover set of solid oxide fuel cell-gas turbine (SOFC-GT) would feature with high electrical efficiency, but contain the highly coupled equipment units for cooling, heating and electricity supplies. Due to such complex nature of multiple supplies and demands, the previously developed control strategies were not suitable, and it is a challenge to develop an appropriate control strategy for the SOFC-GT CCHP system. Therefore, a new approach, called multi-supply-multi-demand (MSMD) control strategy, is proposed in this paper. The MSMD control includes two core algorithms: rolling optimization (RO) and feedback correction (FC). RO is used to determine the operation of energy supply equipment units based on the forecasting weather and loading information of the next 24 h. FC is applied for continual mitigation in case any difference between the actual and predicted energy demands. In the SOFC-GT CCHP system with energy storages for building application, the effectiveness of the MSMD control strategy was tested. It was found that RO could determine the operating schedules of the related equipment units at lower primary energy consumption than the conventional mean, while FC could effectively rectify the prediction errors incurred from the real-time loading conditions.

1. Introduction

Buildings sector is the largest energy-consuming sector, accounting for over one-third of primary energy consumption globally [1]. In general, electricity is supplied and purchased from the city power grid, cooling is provided by the electricity-driven compression chiller (CoC) plant while heating is supplied by primary fuel or electricity. A combined cooling, heating and power (CCHP) system, which consists of a prime mover, a heat exchanger to recover waste heat from the prime mover, a heat-driven absorption chiller (AbC) plant and an auxiliary boiler, can furnish cooling, heating and electricity simultaneously [2]. Due to the heat recovery characteristic of CCHP, the overall energy efficiency can be improved and carbon dioxide emissions can be reduced [3,4]. Solid oxide fuel cell (SOFC) is a high-temperature type with electrical efficiency over 40%. In fact, a bottoming cycle like gas-turbine (GT) can be energized by the unreacted gas fuel from the SOFC, thus the SOFC-GT set can be used as prime mover featuring with high electrical efficiency for the CCHP system [5]. However, it is a challenge to design appropriate control schemes for a SOFC-GT CCHP system, since there are multiple energy supply equipment units with highly coupled nature, and it would be complex in coordination of cooling, heating and electricity generation.

The effective operation of a CCHP system depends on the cooling, heating and electricity demands. Many researches have been carried out to apply suitable control strategies for the CCHP system operation. Two of the most common control strategies are the following electric load (FEL) and the following thermal load (FTL) [6–8]. For FEL control, the electrical energy generated by the prime mover was equal to the electrical energy demand at any moment as long as its capacity can cover. For FTL control, the priority of the prime mover was to satisfy the thermal (both cooling and heating) demands. When the electrical energy demand was large, it resulted in thermal energy surplus under FEL control, or importing electricity from the city power grid under FTL control. When the thermal energy demand was high, it led to operating auxiliary boiler under FEL control or electricity surplus under FTL control. As such, these would decrease the overall energy efficiency of CCHP system due to the changing energy demands throughout a year. To reduce such energy surplus and improve CCHP system efficiency, the following hybrid electric-thermal load (FHL) control strategy has been proposed [3,9–11]. Under FHL control, when the actual ratio of thermal

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Nomenclature

C	capacity (GJ·h^{-1})
COP	coefficient of performance
D_c	cooling demand for building (GJ·h^{-1})
D_e	electricity demand for building (GJ·h^{-1})
D_e'	total electricity demand for building, CoCs and parasitic equipment (GJ·h^{-1})
D_h	heating demand for building (GJ·h^{-1})
D_h'	total heating demand for building and AbCs (GJ·h^{-1})
$DPEC$	daily primary energy consumption (GJ·day^{-1})
e	stored energy (GJ)
$\dot{m}$	mass flow rate (kg·h^{-1})
N	number of SOFC sub-stacks
P	electric power consumption (GJ·h^{-1})
PEC	primary energy consumption rate (GJ·h^{-1})
PLR	part-load ratio
R	load allocation ratio
r	charge/discharge rate (GJ·h^{-1})
RH	relative humidity (%)
T	temperature (°C)
U	on/off state (0 or 1)
$\boldsymbol{X}_{FC}$	vector of control variables of FC
$\boldsymbol{X}_{RO}$	vector of control variables of RO
$\mathbf{X}_{\mathbf{RO}}$	matrix of control variables of RO

Greek symbols

α	supply buffer coefficient
Δ	difference between the actual and predicted values
Δt	time interval (h)
η	efficiency

Subscripts

a	air
b	boiler
c	cooling energy
ch	charge
db	dry-bulb
dch	discharge
dw	drinking water
e	electrical energy
ex	exhaust heat
g	city power grid
h	heating energy
i	inlet
m	methane
max	upper bound
min	lower bound
N	nominal
$para$	parasitic equipment
t	thermal energy
pl	part-load operation
w	water
wb	wet-bulb

Abbreviations

AbC	absorption chiller
ACO	ant colony optimization
AHU	air handling unit
CCHP	combined cooling, heating and power
CoC	compression chiller
CS	cool storage
GT	gas turbine
ES	electricity storage
FC	feedback correction
FEL	following electric load
FHL	following hybrid electric-thermal load
FTL	following thermal load
GA	genetic algorithm
HX	heat exchanger
MPC	model predictive control
MSMD	multi-supply-multi-demand
PSO	particle swarm optimization
RO	rolling optimization
SOFC	solid oxide fuel cell

to electrical energy demand was larger than the thermal to electrical energy capacity of prime mover, the CCHP system would operate in FEL control. Otherwise, it would operate in FTL control. The excess demand for thermal energy would be supplemented by the auxiliary boiler in the former scenario, while that for electrical energy would be made up by the city power grid in the latter. As thermal energy from the auxiliary boiler and electricity from the city power grid were inevitably involved, the overall energy efficiency of the CCHP system was still defeated. Besides, these conventional load-following control strategies seldom accounted for CoC, as well as electricity and thermal storages.

To improve the operating performance, control strategies based on optimization algorithms such as mixed-integer linear programming [12,13], Lagragien relaxation [14], evolutionary algorithm [15], harmony search algorithm [16], Hyper-Spherical search algorithm [17] have been studied. The main principle of these optimization-based control strategies was to solve the objective function of minimizing primary energy consumption, carbon emissions and/or operating cost. Given a set of energy supply equipment units, such as prime mover, AbC, CoC, auxiliary boiler, electricity and thermal storages, the optimization algorithm was implemented to determine the operating parameters of each equipment unit and thus solve the system scheduling problem. Although these optimization algorithms could deal with the complex system like CCHP or microgrid, they were implemented based on the preset schedules of energy demands, which were primarily for design purpose or feasibility study. Obviously, it is not useful for practical CCHP control in response to the actual energy demands.

To tackle the possible uncertainty in energy demands in real situations, control algorithms based on model predictive control (MPC) have been developed [18–27]. MPC was used to forecast cooling, heating and electricity demands, hence to study the performance of the CCHP system. Optimization algorithm was applied at each time step and dynamic performance of the system was considered [19]. However, MPC in these studies were conducted without accounting for the discrepancy between the actual and predicted loading demands. Therefore, they cannot effectively accommodate CCHP system for practical operation. Only a few studies mentioned the solution to handle the prediction errors of energy demands [28–30], but their control strategies were only useful to a single type of energy demand rather than multiple demands. The concept of rolling optimization and feedback correction was introduced in [31], but the planning horizon was 4 h only, which was not sufficient to study the daily characteristic of energy demands. Moreover, the effects of energy storages were not considered in their CCHP system, thus, the potential of load shifting through MPC was not explored.

As a result, the primary objective of this study was to develop a new