Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Dynamic economic dispatch of a hybrid energy microgrid considering building based virtual energy storage system

Xiaolong Jin [a], Yunfei Mu [a,*], Hongjie Jia [a], Jianzhong Wu [b], Tao Jiang [c], Xiaodan Yu [a]

[a] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 30072, China
[b] Institute of Energy, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
[c] School of Electrical Engineering, Northeast Dianli University, Jilin, China

HIGHLIGHTS

- A building based virtual energy storage system (VESS) model was developed.
- A dynamic economic dispatch model integrated with VESS was developed.
- The charging/discharging characteristics of the VESS were analyzed.
- The VESS was dispatched within the customer temperature comfort range.

ARTICLE INFO

Article history:
Received 4 April 2016
Received in revised form 15 July 2016
Accepted 16 July 2016
Available online xxxx

Keywords:
Hybrid Energy Microgrid (H-Microgrid)
Virtual energy storage system (VESS)
Dynamic economic dispatch (DED)
Low-carbon building

ABSTRACT

The increasing complexities of hybrid energy Microgrid (H-Microgrid) integrated with renewable generations, dispatchable distribution generators (DGs) and low-carbon buildings require more intelligent dispatch method. The building sector occupies the main body of the energy consumption, which represents a major potential contributor for reducing the daily operating cost of the H-Microgrid. In this paper, a building based virtual energy storage system (VESS) model was developed by utilizing the heat storage capability of the building. Then, a dynamic economic dispatch (DED) model of the H-Microgrid considering the VESS was developed. Finally, the VESS was integrated into the DED model of the H-Microgrid for daily operating cost reduction. The indoor temperature of the building was adjusted within the customer temperature comfort range to manage the charging/discharging power of the VESS. Numerical studies demonstrate that the proposed DED method can make full use of the available capacity of VESS to reduce the daily operating cost, and guarantee the customer temperature comfort level at the same time.

1. Introduction

With the growing concerns over the energy depletion and environmental issues around the world, increasing attention is being paid to technologies in renewable generation utilization and energy efficiency improvement [1]. According to the U.S. Department of Energy, about 40% of total energy is consumed in buildings in industrialized countries, among which 68% is electricity [2]. As a result, a number of countries have taken specific initiatives to encourage a high penetration of renewables and low energy consumption in their building sectors [2–9]. The European Directive (2010/31/EU) shows that all the new buildings in Europe are required to be nearly zero energy buildings by 2020, targeting a high penetration of renewables and low energy consumption [4]. In China, the building sector currently accounts for 27.6% of the total energy use and is estimated to reach 35% by 2020 [5,6]. The Chinese government has paid particular attention to the retrofits and renovations of the existing buildings, and provided financial support for the energy management in large commercial and public buildings [5,7]. The Building Energy Efficiency consortium in the U.S.-China Clean Energy Research Center (CERC) seeks to address research on building operation economic saving technologies and practices [8,9].

As an effective way to handle the uncertainties of the renewable energies, the H-Microgrid provides an economical energy supply for the buildings [10,11]. The increasing complexities of H-Microgrid integrated with renewable generations, dispatchable distribution generators (DGs) and low-carbon buildings [12] require more intelligent dispatch method. It has been shown that 20–30% of the

* Corresponding author.
E-mail addresses: xljin@tju.edu.cn (X. Jin), yunfeimu@tju.edu.cn (Y. Mu), hjjia@tju.edu.cn (H. Jia), wuj5@cardiff.ac.uk (J. Wu), eetaojiang@gmail.com (T. Jiang), yuxd@tju.edu.cn (X. Yu).

http://dx.doi.org/10.1016/j.apenergy.2016.07.080

Please cite this article in press as: Jin X et al. Dynamic economic dispatch of a hybrid energy microgrid considering building based virtual energy storage system. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.07.080

Nomenclature

Abbreviations

DED	dynamic economic dispatch
VESS	virtual energy storage system
DG	distribution generator
DE	diesel engine
FC	fuel cell
EC	electric chiller
BESS	battery energy storage system

Sets and indices

J, j	set of indexes of the wall orientations of a building
T, t	set of indexes of the dispatch time periods
DG, i	set of indexes of the dispatchable DGs
EC, n	set of indexes of the electric chillers

Parameters and constants

C_{ph}, C_{se}	real-time electricity purchasing/selling prices (\$/MW h)
C_{gas}	natural gas price (\$/MW h)
P_{el}	electric load of the H-Microgrid (kW)
P_{PV}, P_{WT}	electric power generated by photovoltaic/wind turbine (kW)
U_{wall}, U_{win}	heat transfer coefficient of the wall/window in the building [W/(m^2·K)]
$F_{wall,j}$	the area of the total wall surface at the j-wall orientation (m^2)
$F_{win,j}$	the area of the total window surface at the j-wall orientation (m^2)
T_{out}, T_{in}	outdoor/indoor temperature (°C)
T_{set}	indoor temperature set-point (°C)
τ_{win}, SC	the glass transmission coefficient and shading coefficient of the windows
α_w	absorbance coefficient of the wall external surface
$\dot{Q}_{in}$	internal heat gains from people, appliances and lighting (kW)
ρ, C, V	the density (kg/m^3), specific heat capacity [J/(kg·°C)] and volume of the air (m^3) in the building
a, b, c	fuel cost coefficients of the diesel engine
η_{FC}	efficiency of the fuel cell
EER_{EC}	energy efficiency ratio of the electric chiller
η_{ch}, η_{dis}	charging/discharging efficiency of the BESS
CAP_{bt}	the rated capacity of the BESS (kW h)
SOC, δ	the state of charge/self-discharge ratio of the BESS
E_{bt}	the residual energy of the BESS (kW h)
ρ_{DG}, ρ_{su}	maintenance cost (\$/kW h) and startup cost (\$) of a dispatchable DG
R_u, R_d	ramp-up/ramp-down rate of a dispatchable DG (kW/min)
S_u, S_d	startup/shutdown rate of a dispatchable DG (kW/min)
UT, DT	minimum up/down time periods of a dispatchable DG (h)
ρ_{WT}, ρ_{PV}	maintenance cost of the WT and the PV (\$/kW h)
ρ_{bt}, ρ_{EC}	maintenance cost of the BESS and the electric chiller (\$/kW h)

Variables

P_{ex}	electric power exchange with the external grid (kW)
P_{gas}	natural gas purchase (kW)
P_{DE}, P_{FC}	electric power generated by DE/FC (kW)
P_{bt}	charging/discharging power of the BESS (kW)
$\dot{Q}_{EC}$	cooling power generated by the electric chiller (kW)
$\dot{Q}_{cl,building}$	cooling load of the building with VESS (kW)
$\dot{Q}'_{cl,building}$	cooling load of the building without VESS (kW).
P_{DG}	power generation of a dispatchable DG (kW)
U_{DG}	operation status of a dispatchable DG
U'_{DG}, U''_{DG}	startup/shutdown status of a dispatchable DG
T^{on}, T^{off}	number of successive ON/OFF time periods of a dispatchable DG (h)

energy consumption of the building sector, which occupies the main body of the energy consumption of the H-Microgrid, can be saved through economic dispatch without changing the structure and hardware configuration of the H-Microgrid [2].

Several studies have been carried out to investigate the economic dispatch for the H-Microgrid. An economic dispatch model was developed in [2] for a low-carbon building to minimize the total cost of electricity and natural gas. A hierarchical energy management system was proposed in [10] for the H-Microgrid based on an energy hub model. A model predictive control based strategy using nonlinear programming model was proposed to dispatch a building Microgrid under dynamic electricity price [12]. The mixed-integer nonlinear programming model was proposed to solve the economic dispatch problem for a building Microgrid and handle the discrete working ranges of the energy systems [13]. A multi-objective mixed-integer linear programming model was proposed to reduce the daily operating cost and the total emission of the H-Microgrid [14].

The controllable loads of the H-Microgrid, such as the refrigerators, freezers, air conditioners, water heaters, heat pumps and electric vehicles (EVs), *etc.*, can change their normal power consumption patterns to participate in the economic dispatch of the H-Microgrid due to their energy storage and controllable characteristics [15–21]. The charging strategy of the EVs in an office building Microgrid equipped with a photovoltaic (PV) system and a combined heat and power unit was discussed in [18]. In [19], a heuristic operation strategy for a commercial building Microgrid containing EVs and a PV system was proposed to improve the self-consumption capability of PV energy. An economic dispatch model is proposed for a residential Microgrid including a charging spot with a Vehicle-to-Grid system and renewable energy sources to reduce the daily operating cost [20]. A multi-objective dispatch model is proposed for a Microgrid containing EVs, responsive loads and renewable generations to reduce the daily operating cost and the total emission [21].

The existing research works have made good contributions to the economic dispatch of H-Microgrid. However, the coupling relationship among the heating/cooling demand of a building, the customer temperature comfort range and the outdoor temperature are not well considered in the economic dispatch of the H-Microgrid. Actually, the heating/cooling demand of a building can be adjusted in the economic dispatch process to reduce daily operating cost without disturbing the temperature comfort level of the building. For this purpose, the mathematical relationship among the indoor temperature, cooling demand and outdoor temperature is established in this paper based on the building thermal equilibrium equation. Then, a building based virtual energy storage system (VESS) model was developed as a dispatchable unit to participate in the economic dispatch of the H-Microgrid for daily operating cost reduction.

On the other hand, the economic dispatch of H-Microgrid can be divided into static economic dispatch and dynamic economic dispatch (DED) [22–24]. Compared with static economic dispatch,