Energy and Buildings 90 (2015) 65–75

Contents lists available at ScienceDirect

Energy and Buildings

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

Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system

Faeze Brahman, Masoud Honarmand, Shahram Jadid*

Center of Excellence for Power System Automation and Operation, Department of Electrical Engineering, Iran University of Science and Technology, P.O. Box 1684613114, Tehran, Iran

ARTICLE INFO

Article history:
Received 31 August 2014
Received in revised form 3 November 2014
Accepted 21 December 2014
Available online 31 December 2014

Keywords:
Combined cooling heating and power (CCHP)
Energy hub
Demand response (DR)
Plugged in hybrid electric vehicle
Thermal energy storage

ABSTRACT

Energy crisis along with environmental concerns are some principal motivations for introducing “energy hubs” by integrating energy production, conversion and storage technologies such as combined cooling, heating and power systems (CCHPs), renewable energy resources (RESs), batteries and thermal energy storages (TESs). In this paper, a residential energy hub model is proposed which receives electricity, natural gas and solar radiation at its input port to supply required electrical, heating and cooling demands at the output port. Augmenting the operational flexibility of the proposed hub in supplying the required demands, an inclusive demand response (DR) program including load shifting, load curtailing and flexible thermal load modeling is employed. A thermal and electrical energy management is developed to optimally schedule major household appliances, production and storage components (i.e. CCHP unit, PHEV and TES). For this purpose, an optimization problem has been formulated and solved for three different case studies with objective function of minimizing total energy cost while considering customer preferences in terms of desired hot water and air temperature. Additionally, a multi-objective optimization is conducted to consider consumer’s contribution to CO_2, NO_x and SO_x emissions. The results indicate the impact of incorporating DR program, smart PHEV management and TES on energy cost reduction of proposed energy hub model.

1. Introduction

Recently, environmental issues such as increasing level of pollutant emissions along with the rapid growing of energy demand and the surge in fuel cost has drawn particular attention to distributed energy resources (DERs). DERs contribute to system by cutting the expenses and being more environmental friendly in comparison with centralized power systems. In this regard, combined heat and power (CHP) units are one of the most beneficial technologies and their performance will precisely be clarified in this paper. The main advantage of a CHP unit is its potential of generating both power and heat simultaneously. Accordingly, the whole system efficiency is improved by using the wasted heat to satisfy the heating demand. Moreover, combined cooling, heating and power units (CCHPs) are becoming widely desirable and even more economical due to the fact that they can meet the cooling demand along with electrical and heating one. As stated in [1], efficiency of CCHP system is up to 60–80%, which is considerably higher than those of traditional energy supply systems. Although, CCHPs can reach their highest capabilities in residential and commercial sectors, their collaboration with the upstream grid, by providing reserve and peak shaving services, are beyond doubt [2].

Several studies have proposed optimal operation of CCHPs with regard to electrical, heating and cooling demand as well as economic and environmental consideration [3–6]. The authors in [7], presented mathematical models of a CCHP components, then a multi-objective optimization has been formulated so as to minimize energy cost and greenhouse gas emissions of a commercial Micro-Grid (MG). In this respect, “Energy Hub” concept has been firstly initiated at ETH Zurich [8]. As defined in [9], an Energy Hub is an integrated system with multiple energy carriers at its input where energy production, conversion and storage technologies such as CCHP, renewable energy resources and batteries are deployed in order to supply certain required services such as electricity, heating and cooling at its output.

The application of CCHP systems accompanied by photovoltaic (PV) systems can enhance the system overall performance particularly in residential energy hubs. Albeit the efficacy of PV and other DERs has been proved, their unsteady nature poses big challenges to the operation of power systems. Several candidate solutions have been proposed to address this issue. Energy storage systems (ESSs)

---

* Corresponding author. Tel.: +98 21 77491223; fax: +98 21 77491242.
E-mail addresses: faeze_brahman@elec.iust.ac.ir (F. Brahman), honarmand@elec.iust.ac.ir (M. Honarmand), jadid@iust.ac.ir (S. Jadid).

http://dx.doi.org/10.1016/j.enbuild.2014.12.039
0378-7788/

Sets

t	time interval $t \in \{1, \ldots, 24\}$
T_i	desired time window of appliance i $T_i = [\alpha_i, \beta_i]$
i	index of appliances
A	set of shiftable appliances $A = \{wm, dw, dry, pp, ir\}$

Subscripts

MRH	must run hours of appliance
MUT	minimum up time of appliance
$crit$	critical

Constants

η_e,η_{th}	electrical and thermal efficiency of CCHP unit
β	converting factor of 1 kWh to m^3 natural gas.
P_{cchp}^{min}, P_{cchp}^{max}	minimum and maximum electrical output of CCHP
H_{cchp}^{min}, H_{cchp}^{max}	minimum and maximum thermal output of CCHP
rr_e	electrical ramp rate of CCHP (kW/h)
S	PV array area (m^2)
I	solar radiation (kW/m)
IL_{out}^t	outdoor illumination at time t
IL_{req}^t	required illumination at time t
T_{cw}	temperature of entering cold water (°C)
V	water storage volume (L)
C_{air}	heat capacity of air (kWh/°C)
V_{cold}^t	volume of entering cold water (L)
C_{water}	specific heat of water (kWh/°C)
R	thermal resistance of the house shell (°C/kW)
T_{ws}^{des}	desired temperature of water storage (°C)
T_{ws}^{min}, T_{ws}^{max}	minimum and maximum water storage temperature deviation
T_{in}^{des}	desired indoor temperature (°C)
T_{in}^{min}, T_{in}^{max}	minimum and maximum indoor temperature deviation (°C)
T_{out}^t	hourly outdoor temperature (°C)
η_{in}, η_{dr}	injecting and drawing heat efficiencies
Cap	PHEV's battery capacity (kWh)
P_{li}	rated power of lighting (kW)
N	number of shiftable loads
π_{TOU}^t	time-of-use price tariff at time t
π_{NG}	natural gas price
$\mu_{net}^{CO_2,NO_x,SO_x}$	emission factors of network electricity
$\mu_f^{CO_2,NO_x,SO_x}$	emission factors of natural gas

Variables

P_{cchp}^t	CCHP electrical output at time t
H_{cchp}^t	recovered heat from PGU at time t
F_{cchp}^t	fuel consumption of CCHP at time t (m^3)
IL_{in}^t	indoor illumination level at time t
T_{ws}^t	water storage temperature at time t (°C)
T_{in}^t	indoor temperature at time t (°C)
P_{net}^t	exchange power with network at time t (kW)
H_{ws}^t	exchange heat with water storage at time t
H_{air}^t	required thermal energy to set the home temperature at time t (kWh)
H_{in}^t, H_{dr}^t	injected/drawn heat from TES at time t(kWh)
Q_{tes}^t	TES energy content at time t(kWh)
$P_{ch,phev}^t$	PHEV's battery charging (kW)
$P_{dch,phev}^t$	PHEV's battery discharging (kW)
D_{Etotal}^t	total electrical demand at time t (kW)
D_{crit}^t	critical electricity demand at time t (kW)
E_{EC}^t, H_{AC}^t	electricity and heat supplied to electric and absorption chiller at time t

Binary variables

s_{cchp}^t	CCHP on/off status at time t
s_i^t, u_i^t, d_i^t	on/off, start up and shut down status of appliance i
u_{in}^t, u_{dr}^t in_t	injecting/drawing state of TES at time t
ch_{phev}^t, dch_{phev}^t	PHEV's battery charging/discharging state

are being installed to reduce the mismatch between energy supply and demand. Recent developments in energy storage technologies have introduced Plug-in Hybrid Electric Vehicle (PHEV) as a decent solution [10,11]. Smart building and PHEV are two promising technologies. The integration of these two emerging technologies holds great promises in improving the power supply reliability and the flexibility of building energy and comfort management [12]. The owner of a PHEV usually use the vehicle for a couple of hours during a day and the vehicle is available in the home garage for the rest of the day. Hence, PHEV's battery can be considered as ESS [13–15]. In a building integrating DERs, PHEVs can contribute to the system by charging or discharging that are called grid-to-vehicle (G2V) and vehicle-to-grid (V2G), respectively [16].

According to [17] an indisputable fact about micro-CHP-based building is to accurately coordinate its thermal and electrical loads. Therefore, an energy management system (EMS) is established as a promising mean to optimally coordinate all generation, consumption and energy storage resources. Various studies have been conducted to develop the EMS model and to demonstrate its advantages by serving both economic and technical facets. Ref. [17] has proposed a smart scheduling of a micro-CHP based MG and a temperature dependent thermal load modeling. Several uncertainties associated with temperature, electrical and thermal load are considered in the proposed model. A smart EMS has been presented in [18] incorporating power forecasting module, ESS, and optimization module to achieve a great coordination between power production of DG units and ESS.

The urge to manage the unpredictability of RESs caused a great interest in the deployment of Demand Response (DR) programs [19]. As defined in [20], "DR is when consumers voluntarily change their energy consumption pattern from their nominal one, in response to price signal variations or when motivated by incentive payments offered by utilities in order to maintain the system reliability during on-peak periods". It can be concluded that DR programs not only benefit participated consumers with incentive payments as well as bill savings, but also the utilities by enhanced system reliability, modified load shape and better market performance [21]. The impact of Demand Side Management (DSM) programs on systems incorporating renewable energy resources has been addressed in several studies [22,23]. In [23] a Demand Response Provider (DRP) aggregates customer load reduction offers and a stochastic method has been used to capture wind and solar power uncertainties as well as demand forecast errors. The authors in [24] proposed a stochastic model to schedule both energy and reserve by generating units and responsive loads. The applied DR programs helped to cover uncertainties associated with wind power forecasting. Economic value of an extended energy hub with heat DSM capability is determined in [25] based on Monte Carlo simulation.

In this regard, this paper aims at presenting an optimal energy management strategies for a residential energy hub in order to well coordinate CCHP unit, PV panels, PHEV and Thermal Energy Storage