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Demand side management for a residential customer in multi-energy systems

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ABSTRACT

Today, as a consequence of the growing installation of efficient technologies, e.g. micro-combined heat and power (micro-CHP), the integration of traditionally separated electricity and natural gas networks has been attracting attentions from researchers in both academia and industry. To model the interaction among electricity and natural gas networks in distribution systems, this paper models a residential customer in a multi-energy system (MES). In this paper, we propose a fully automated energy management system (EMS) based on a reinforcement learning (RL) algorithm to motivate residential customers for participating in demand side management (DSM) programs and reducing the peak load in both electricity and natural gas networks. This proposed EMS estimates the residential customers' satisfaction function, energy prices, and efficiencies of appliances based on the residential customers' historical actions. Simulations are performed for the sample model and results depict how much of each energy, i.e. electricity and natural gas, the residential customer should consume and how much of natural gas should be converted in order to meet electricity and heating loads. It is also shown that the proposed RL algorithm reduces residential customer energy bill and electrical peak load up to 20% and 24%, respectively.

1. Introduction

CHP systems are getting increased interest in a growing number of countries. Today, the concentration of micro-CHP market is in mission-critical operations like research institutions, hospitals, and data centers. However, some manufacturers with aid of governments, proved that application of micro-CHP in home would be a financially viable option (Cho, Luck, Eksioglu, & Chamra, 2009).

The market of domestic micro-CHP is growing rapidly (Ellamla, Staffell, Bujlo, Pollet, & Pasupathi, 2015). An estimated 138,000 fuel cell micro-CHP systems had been installed in Japan by the end of 2014 (Ellamla et al., 2015). The Japanese government set a target of 1.4 million micro-CHP systems; South Korea's target is 1 million and the European Union's target is 50,000 micro-CHP systems installed by 2020 (Ellamla et al., 2015).

By raising the use of CHP systems in a near future, synergy effects of coupling between electricity and natural gas networks draw researchers' attention to propose an integrated picture of these two physically separated networks (Geidl et al., 2007). To have this integrated picture and in order to model the interaction of these two networks properly in Mancarella (2014), an appropriate framework for a multi-energy system (MES) has been proposed.

As a simple definition, MES is whereby electricity, heating, fuels, and other type of energies optimally interact with each other at various levels. This approach of modeling creates an important opportunity to increase technical, financial, and environmental performance relative to conventional energy systems where energy systems, e.g. natural gas and electricity, are treated independently.

Along with the development of MES, smart grid concepts have been also grown. To realize smart grid concepts, demand side management (DSM) programs play a leading role. DSM commonly refers to the methods implemented by utility companies for reducing or shifting the energy consumptions at the residential customers' side (U.S. Federal Energy Regulatory Commission, 2008).

To implement DSM techniques, the residential customer should be equipped with bidirectional communication system. There are two main approaches in DSM; direct load control (Gomes, Antunes, & Martins, 2007; Wang, Rahimi, & Xu, 2011) and smart pricing techniques (Mohsenian-Rad, Wong, Jatskevich, Schober, & Leon-Garcia, 2010; Samadi, Mohsenian-Rad, Schober, & Wong, 2012). In the first method, utilities are authorized to remotely control the residential customers' energy consumptions. Alternatively in smart pricing, utilities encourage residential customers to

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Nomenclature

Indices

t	the time interval index
ω	the household appliances index

Appliances abbreviations

WM	washing machine
DW	dishwasher

Sets

Ω	shiftable appliances; $\Omega = \{\text{WM, DW}\}$
Π_e	the set of possible electricity price
Π_g	the set of possible natural gas price
S	the set of possible state signal

Functions

$f_\omega(\cdot)$	dissatisfaction cost function of shiftable appliance ω
$f_{eP}(\cdot)$	dissatisfaction cost function of PHEV
$q_1(\cdot)$	the possibility function of connecting PHEV at different time
$q_2(\cdot)$	the possibility function of disconnecting PHEV at different time

Variables

$P_e^{out}(t)$	output electrical energy flow of MES (kWh)
$P_h^{out}(t)$	output heating energy flow of MES (kWh)
$P_c^{out}(t)$	output cooling energy flow of MES (kWh)
$P_{th}^{out}(t)$	summation of boiler and CHP thermal generations (kWh)
$P_e^{in}(t)$	input electrical energy flow of MES (kWh)
$P_g^{in}(t)$	input natural gas energy flow of MES (kWh)
$P_{gC}^{in}(t)$	input natural gas flow of CHP (kWh)
$P_{gB}^{in}(t)$	input natural gas flow of the boiler (kWh)
$P_{eP}^{in}(t)$	imported electrical energy to the PHEV (kWh)
$P_{eP}^{out}(t)$	exported electrical energy from the PHEV to the grid (kWh)
$SOC(t)$	PHEV state of charge
$L_e^{ct}(t)$	electrical controllable loads (kWh)
$L_e^{mr}(t)$	electrical must-run loads (kWh)
PAR_i	peak to average ratio of energy source $i \in \{e, g\}$
$Y(t)$	total dissatisfaction cost
$Y_1(t)$	all dissatisfaction effects associating with different appliances
$Y_2(t)$	the dissatisfaction due to PHEV
$y_\omega(t)$	the residential customers' dissatisfaction caused by appliance ω
$z_\omega(t)$	delay from request time of appliance ω
$z_{eP}(t)$	the connection status of PHEV
$u_\omega(t)$	action signal of appliance ω at time t, binary; "on"/"off"
$u_{eP}(t)$	a variable within $[-1, 1]$ presenting the operation of the PHEV
$u_{CHP}(t)$	a variable within $[0, 1]$ determining different generation levels of CHP
$J(t)$	total cost function (\$)
$J_{Monetary}(t)$	total monetary cost (\$)
$J_{non\text{-}Mon}(t)$	total non-Monetary cost (\$)
$\pi_e(t)$	electricity price per hour (\$/kWh)
$\pi_g(t)$	natural gas price in one hour (\$/kWh)
$\vec{s}(t)$	state signal at time t
$\vec{u}(t)$	the vector of action signal at time t
$\chi(\vec{s}, \vec{u})$	EMS policy
$V^\chi(\vec{s})$	value of state $\vec{s}$ under policy χ
$V^*(\vec{s})$	optimal value function
$Q^\chi(\vec{s}, \vec{u})$	Q-function
$\chi^*(\vec{s}, \vec{u})$	optimal policy

Parameters

Δt	one time slot duration, i.e. 0.1 h
l_ω	the consumption of appliance ω in one time slot (kWh)
ν_ω	the importance of appliance ω determined by the residential customers
p_k^ω	transition probabilities of appliance ω for all $k \in \{0, 1, 2, 3\}$
WID_ω	maximum delay of appliance ω
η_{ee}^T	transformer efficiency
η_{gh}^B	boiler efficiency
η_{hc}^A	absorption chiller efficiency
η_{ge}^C	electrical efficiency of the CHP
η_{gh}^C	thermal efficiency of the CHP
η_{e+}^P	PHEV charging efficiency
η_{e-}^P	PHEV discharging efficiency
η_{eL}^P	a parameter within [0, 1] that models losses of the battery during the time slots
$\overline{P_{eP}^{in}}$	maximum charging rate of PHEV (kWh)
$\overline{P_{eP}^{out}}$	maximum discharging rate of PHEV (kWh)
$\overline{E_e}$	maximum charging level of the PHEV (kWh)
SOC_{min}	minimum PHEV state of charge
$\overline{P_{gC}^{in}}$	maximum rate of natural gas to the CHP (kWh)
$\overline{P_{gB}^{in}}$	maximum rate of natural gas to the boiler (kWh)
$\overline{P_{hA}^{in}}$	maximum rate of thermal energy to the absorption chiller (kWh)
$\overline{P_{eT}^{in}}$	size of the transformer (kVA)
t_{out}	the time of disconnecting PHEV from the grid
t_{in}	the time of connecting PHEV to the grid
t_{out}^+	maximum of T_{out}
t_{in}^+	maximum of T_{in}
t_{out}^-	minimum of T_{out}
t_{in}^-	minimum of T_{in}
$t_{rq-\omega}$	request time of appliance ω
$\lvert \Pi_e \rvert$	number of possible electricity price
$\lvert \Pi_g \rvert$	number of possible natural gas price
N_u	number of actions in each state
ε	probability of exploration; $0 < \varepsilon < 1$
γ	discount rate; $0 < \gamma < 1$
α	learning rate; $0 < \alpha < 1$

voluntarily manage their loads, e.g. by reducing their consumptions at peak hours on a real time pricing (RTP) market. As there are not direct external forces in the latter approach, residential customers individually decide whether they participate in the DSM program or not. Therefore in this scheme, residential customers can manage their satisfaction and keep it in a standard level.

DSM in MES was introduced in Sheikhi, Rayati, Bahrami, and Ranjbar (2014, 2015) which was called integrated DSM (IDSM). In this approach, consumers can communicate with both networks simultaneously.

In MES, for controlling and optimizing the consumption of a price taker residential customer who has no considerable effect on electricity price, different methods have been introduced and