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Load management in a residential energy hub with renewable distributed energy resources

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ABSTRACT

This paper presents a residential energy hub model for a smart multi-carrier energy home consisting of plug-in hybrid electric vehicle (PHEV), combined heat and power (CHP), solar panels, and electrical storage system (ESS). The energy hub inputs are electricity and natural gas that provide electrical and heat demands at the output ports. In this paper, an optimization-based program is proposed to determine the optimal operation mode of the energy hub, to manage the energy consumption of responsive appliances, to schedule charging/discharging of PHEV and the storage system, and to coordinate solar panels operation with household responsive demand in response to day-ahead time-varying tariffs of electricity. The objective function is to minimize customer payment cost considering vehicle to grid (V2G) capability. Different case studies are conducted to probe the effectiveness of the proposed method and study the impacts of different electrical time-differentiated tariffs on the optimization results on daily and yearly basis.

1. Introduction

Accommodating the distributed energy resources (DERs) and storage options, activating the customer participation in the utility and ISO programs, employing modern technologies, and facilitating two-way flow of energy and information are the main consequences of realizing smart grid [1]. At the residential customer level, smart home appears as a small sample of smart grid to pursue the abovementioned goals. Smart home is a residential building/home equipped with devices synchronized with each other using communication channels in order to manage household energy consumption, provide customer comfort and security, and provide home-based health care. In the context of the energy management, demand response (DR) programs have been proposed to realize a smart home [2]. Several references certify that proper application of residential DR programs not only benefits the system operators by preventing probable system failure, but also provides an opportunity for customers to track their energy prices and consumption, which can lead to lower costs [3–5]. In this regard, home load management (HLM) is designed as an automatic program to facilitate the implementation of residential price-based DR programs. In HLM, a home load controller can automatically manage household controllable load in response to price changes, taking into account customer satisfaction [3,6,7]. Accordingly, household appliances are divided into two classes of responsive and nonresponsive to time-differentiated pricings. In addition to usual appliances, plug-in hybrid electric vehicles (PHEVs) and storage systems have recently penetrated into smart homes. Although utilities became concerned about the challenges associated with multiple domestic PHEV charging activities, PHEV charging control algorithms can lessen these concerns [8,9]. In addition, vehicle to grid (V2G) capability of PHEVs and storage systems, i.e. returning the stored energy to the grid, can bring environmental and economic benefits to the system operators and customers [10,11]. To achieve more benefits from the presence of PHEV and storage system, charge and discharge cycling of them should be optimally scheduled in conjunction with the implementation of HLM programs [3].

Smart home applications drive the increasing need to develop small-scale renewable DERs (RDERs) like new wind or solar power generators [12,13]. These resources are fast improving, reaching a close parity with the conventional generation from the economic perspective [14]. Such resources impose significant investment

Abbreviations: CHP, combined heat and power; DR, demand response; DER, distributed energy resource; EV, electric vehicle; HLM, home load management; IBR, inclining block rate; PHEV, plug-in hybrid electric vehicle; RDER, renewable distributed energy resource; TOU, time of use.

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Nomenclature

Sets and indices

M	set of on/off controlled appliances
m	index of on/off controlled appliances
N	set of consumption level controlled appliances
n	index of consumption level controlled appliances
t	hour index

Parameters, variables, and functions

b_m	first hour of allowable operation interval for appliance m
b_n	first hour of allowable operation interval for appliance n
Cost	total energy cost for the customer in the next day [¢]
c^{PH}	last hour of daily trip
C_{CHP}^{max}	maximum allowable natural gas input of CHP [kW]
cap^s	ESS capacity [kW h]
ch_{max}^S	maximum allowable charging rate of ESS at each hour [kW]
cap^{PHEV}	PHEV battery capacity [kW h]
ch_{max}^{PHEV}	maximum allowable charging rate of PHEV at each hour [kW]
dch_{max}^{PHEV}	maximum allowable discharging rate of PHEV at each hour [kW]
dch_{max}^S	maximum allowable discharging rate of ESS at each hour [kW]
$E_{grid}(t)$	electrical power provided by grid at hour t [kW]
$E_{RDER}(t)$	electrical power provided by RDER at hour t [kW]
$E_{CHP}(t)$	electrical power provided by CHP at hour t [kW]
$E_{dch}^{PHEV}(t)$	in-home discharging energy of PHEV at hour t [kW h]
$E_{dch}^S(t)$	discharged energy of ESS at hour t [kW h]
$E_{app}(t)$	energy consumption of electrical household appliances at hour t [kW h]
$E_{ch}^S(t)$	charging energy of ESS at hour t [kW h]
$E_{ch}^{PHEV}(t)$	in-home charging energy of PHEV at hour t [kW h]
$E_{V2G}(t)$	amount of energy returned to the grid at hour t [kW h]
E_{min}^{PHEV}	minimum allowable charge state of PHEV [kW h]
E_{min}^S	minimum allowable charge state of ESS [kW h]
E_f^S	final charge state of ESS in a day [kW h]
E_0^S	initial charge state of ESS in a day [kW h]
$E_m(t)$	energy consumption of appliance m at hour t [kW h]
E_m	energy consumption of appliance m at each operating hour [kW h]
$E_n(t)$	energy consumption of appliance n at hour t [kW h]
E_n	total electrical energy consumption of appliance n in its operation interval [kW h]
$E_n^{min}(t)$	minimum allowable energy consumption of appliance n at hour t [kW h]
$E_n^{max}(t)$	maximum allowable energy consumption of appliance n at hour t [kW h]
$E_{app}^R(t)$	responsive appliances' energy consumption at hour t [kW h]
$E_{app}^{NR}(t)$	non-responsive appliances' energy consumption at hour t [kW h]
E_0^{PHEV}	initial charge state of PHEV in a day [kW h]
E_f^{PHEV}	final charge state of PHEV in a day [kW h]
E_{out}	expected electrical energy consumption during daily trip [kW h]
$G(t)$	received natural gas at energy hub input at hour t [kW h]
g^{PH}	first hour of daily trip
$H_d(t)$	total household heat demand at hour t [kW]
$H_{CHP}(t)$	heat power provided by CHP at hour t [kW]
IBR_{th}	hourly IBR tariff threshold [kW]
$I_m(t)$	binary indicator of operation of appliance m, which is 1 when appliance m is on at hour t
l_m	last hour of allowable operation interval for appliance m
l_n	last hour of allowable operation interval for appliance n
$PH(t)$	PHEV charge state at the end of hour t [kW]
$R(t)$	solar radiation at hour t [W/m^2]
S	solar panel surface area [m^2]
$S(t)$	ESS charge state at the end of hour t [kW h]
$T(t)$	solar panel temperature at hour t [°C]
U_m	required operation time of appliance m in the day [h]
η	solar panel conversion efficiency of photovoltaic array
η_{ch}^S	efficiency of ESS charging
η_{ch}^{PHEV}	efficiency of PHEV battery charging
η_{dch}^S	efficiency of ESS discharging
η_{dch}^{PHEV}	efficiency of PHEV battery discharging
$\eta_{DC/AC}$	efficiency of DC/AC converter beside RDER
η_{eapp}	efficiency of household electrical appliances
η_{gapp}	efficiency of household gas-consuming appliances
η_{g-h}	gas to heat conversion efficiency of CHP
η_{g-e}	gas to electricity conversion efficiency of CHP
$\lambda_g(t)$	natural gas tariff at hour t [¢/kW h]
$\lambda_e(t)$	electricity tariff at hour t [¢/kW h]
$\nu(t)$	dispatch factor of natural gas at hour t

cost and negligible operation cost to the customer. So, if they are installed at a home, they should be optimally utilized to maximally benefit the customer. This can be achieved by coordinating between the demand and RDERs generation. Therefore, operation of RDER and responsive demand should be synchronized with each other in a smart home [15].

Along with the proliferation of smart home concepts, combined heat and power (CHP) technology, has become popular at homes due to the expansion of natural gas networks and benefits of this energy carrier [16]. Advent of CHP and other converters between different energy carriers makes the analysis of residential energy system more complicated. The *energy hub* model has been recently presented to simplify the analysis of such multi-carrier energy systems [17,18].

Energy hub can be identified as a unit with in- and output ports that transmits, converts and stores multiple energy carriers. Typically, energy hubs receive common energy carriers such as electricity and natural gas at input ports and supply electrical and heat demands at output ports. In a smart multi-carrier energy home, CHP, PHEV, and storage system can act as the hub components. This paper presents a *residential energy hub* model for such a smart home incorporating RDERs. Studies on the energy hub concept, modeling, and operation have recently seen a growing trend. The main operational question is about the dispatch of received energy carriers into the energy hub components. Various algorithms have been proposed in previous studies to optimally solve the energy hub operation problem [15,17,18].