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Residential load management in an energy hub with heat pump water heater

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HIGHLIGHTS

- Energy hub with active controllable load and generation.
- Load shifting due to optimal scheduling of appliances.
- Reduction of power from grid due to PV-Battery system and CHP.
- A proposal that gives predictions on optimal control settings for actual implementation.
- Utilities- saving power, users- monetary savings and the environment-CO_2 mitigation.

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ABSTRACT

Today, as a consequence of the growing installation of efficient technologies, such as combined heat and power (CHP) as a co-generation, the integration of electricity through grid supply, Photovoltaic (PV) and energy storage systems as an integrated network is attracting a lot of attention in smart grid applications. To model the interaction among electricity and natural gas, the energy hub framework is adopted to determine a modelling procedure for such multi-carrier energy systems. This paper presents a residential energy hub model for a smart home as a modified framework of conventional energy hubs in a smart grid with consideration of heat pump water heater, coordination of sources and carbon emissions. Therefore, this study is twofold; the first part optimizes the operation of the combined CHP, Photovoltaic and storage system under dynamic pricing. Since residential load management plays a key role in realizing household demand response programs in a smart grid, performing optimal load management in the proposed residential energy hub model is also studied in this paper. To achieve this, the optimization problem is extended by considering modelling of a heat pump water heater. It is also found out that CO_2 signal could give customers an environmental motivation to shift or reduce loads during peak hours, as it would enable co-optimization of electricity consumption costs and carbon emissions reductions.

1. Introduction

Electrical energy hub describes the relation between in and outputs of energy flows. Generally, in the hub; multiple energy carriers like electricity, gas and heat can be converted, conditioned and if available also stored [1]. Thereby, a hub can model a single building, a city or a whole country. In smart grid applications, residential energy hub is a platform that is used to facilitate residential demand response (RDR) in the presence of renewable energy resources and storage systems. It provides electrical power demand reduction while also giving added value to residential consumers.[1] The optimization of energy consumption, with consequent cost reduction, is one of the main challenges for the present and future smart grid [2]. In this work, residential energy hub is studied under time differentiated electricity price using optimization approach.

Optimization approach in a residential hub is primarily concerned with optimal control of residential loads, supply resources and storage systems [3,4]. The modelling takes into account the consumer's preferences. In [5], the authors model home load management in a residential energy hub with resources as combined heat and power (CHP) and electricity grid with plug-in hybrid electric vehicle (PHEV) as the charging and discharging device. A mixed integer linear programming

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Nomenclature

Indices

i	appliances index
t	an index of the time period
ω	an index of weighting factors
k	an index of flexible appliances
j	an index of night time loads

Sets

A	a set of all household appliances
N	the control horizon (24 hrs)
K	a set of flexible appliances
J	a set of night time loads

Parameters

t_s	sampling time (15 mins)
P_i	rated power of appliance i (kW)
N_k	duration of appliance k being on (mins)
ρ_t	time-of-use electricity (TOU) price at time t (R)
C	the maximum cost that the consumer is willing to pay (R)
$d_k i$	the on-time start of appliance k
e_k	the on-time end of appliance k
$u_{k,t}^{bl}$	baseline commitment status of appliance k at time t
P_t^{inflex}	power consumed by inflexible appliances (kW)
P_{hp}	rated power demand of the heat pump (kW)
COP	coefficient of performance
T_{low}, T_{up}	lower and upper temperature of hot water inside the tank (°C)
T_a	ambient temperature (°C)
T_o	initial temperature of hot water (°C)
$T_{in}(t)$	inlet cold water temperature (°C)
R	South African rands (1R = 0.074 USD as of 22.09.2015)
$p(t)$	time-of-use electricity price (R/kW h)
N	total number of sampling intervals
t_s and k	sampling time (hour) and k^{th} sampling interval respectively
η_{CHP_e}	CHP electrical efficiency
η_{CHP_e}	CHP thermal efficiency
DOD	depth of discharge
η_c	battery's charging efficiency
η_d	battery's discharging efficiency
E_0	the initial state of charge of the battery at time t
E^{min}	minimum allowable battery capacity (kW h)
E^{max}	maximum allowable battery capacity in (kW h)
λ_c	the carbon emission price (R/kg)
$M_{c,t}$	mass of carbon dioxide emission (kg)
α_{grid}	CO_2 emission rate of the grid (kg/kW h)
$Rand(R)$	South African currency ($1Rand = 0.089$ USD), as at 10.11.2016.
Q_L	total standby (convectional) losses
q_{loss}	convention losses in (W/m^2)
Δx	Insulation thickness (m)
h	surface heat transfer coefficient (W/m^2 K)
$\varkappa$	thermal conductivity (W/m K)
S_{area}	total surface area (m^2)
c	specific heat capacity of water (J/kg °C)

Variables

Q_D	thermal loss due to hot water demand
$W_D(t)$	hot water flow rate or water demand (litres/hour)
$T(t)$	Temperature of the hot water (°C)
$u_{k,t}$	optimal commitment status of the k^{th} flexible appliance at time t
$u_{j,t}$	optimal commitment status of the j^{th} night time appliance at time t
$u(t)$	heat pump switch (0 or 1)
$\o$	diameter (m)
$\dot{T}$	derivative of temperature
L	total mass of water in the tank (kg)
E_t	energy status of the battery t (kW h)
$P_{b,t}$	the battery charging power (kW)
$\bar{P}_{b,t}$	the battery power discharged (kW)
$P_{g,t}$	grid power at every time (kW)
P_t^{flex}	power consumed by flexible appliances (kW)
P_t^{ngt}	power consumed by night time appliances (kW)
$P_{A,t}$	power demanded by all appliances excluding battery at time t (kW)

(MILP) problem is formulated with the load classified as responsive and non-responsive appliances without consideration of carbon emissions. In [6,7], optimal operation of residential energy hubs in smart grids is studied with consideration of carbon emissions. The disparity lies in the MILP with extensive modelling of different types of appliances in a household taking into account consumer's comfort level [6].

General micro-grid studies have been conducted in [8–17]. However, the difference between micro-grid, energy hubs and virtual power plants has been presented in [1] and the purpose of this work is to advance research on energy hubs. However, some of the knowledge on modelling some components of energy hubs such as renewable sources, storage and loads can be borrowed from micro-grid modelling.

Research on energy hubs is very active presently and notable efforts have been made on modelling and optimization of the operation of such systems. Residential load modelling is generally dealt with under residential demand response [3,17,18]. The study on micro-grid and hubs under demand response are carried out with consideration of carbon emissions in [19,20]. Study on sizing and optimising CHP for residential applications is carried out in [21–26] both with and without DR. Economic evaluation of micro-CHP is carried out in [27,28]. The study on operation of energy hubs can be conducted in two ways; economic dispatch (ED) within the hub and ED between hubs [29].

Although over the years, many countries around the world have implemented rooftop PV systems, many like South Africa, such small-scale renewable systems are not yet integrated to the main grid because of lack of advanced technology and policies that can necessitate grid interconnection [30]. This is the motivation for this work to consider a household with dedicated solar PV and storage systems, without in-feed to the grid.

The motive of this paper is to formulate a practical optimal control model for ED within a hub with modelling of appliances with a heat pump and coordination of all considered resources. The heat pumps are the future energy-efficient devices and when coupled with domestic appliance scheduling can yield great success in demand side management (DSM) [31]. In this work, the problem is modelled as mixed integer nonlinear programming (MINLP) problem as compared to most literature which has presented the problem as a simplified linear problem, hence foregoing some of important sub-models and constraints of the problem and rendering the models far from reality. Therefore our work models a practical situation that gives precise predictions on optimal control settings for actual implementation. This is the contribution of this work to the general research area of residential energy hubs for smart grid applications.

The remainder of this paper is organized as follows: Sections 2