Electrical Power and Energy Systems 79 (2016) 150–160

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Combined residential demand side management strategies with coordination and economic analysis

Ditiro Setlhaolo [*], Xiaohua Xia

Centre of New Energy Systems, Department of Electrical, Electronic and Computer Engineering, University of Pretoria, South Africa

ARTICLE INFO

Article history:
Received 31 August 2015
Received in revised form 23 November 2015
Accepted 2 January 2016
Available online 16 January 2016

Keywords:
Residential demand response
Appliance scheduling
PV system
Storage system
Carbon emissions
Economic analysis

ABSTRACT

In this paper combined demand side management strategy for residential consumers is studied for five households in South Africa. This study is twofold; the first part proposes an energy management system that combines demand side management strategies with a view of minimizing the consumer's cost and reducing the power consumption from the grid. Appliance scheduling with a dedicated photovoltaic and storage system under time-of-use tariff shows that customers can realize cost savings and the power demanded from the grid is reduced by optimal scheduling of power sources. In the second part of this study, a model is developed to investigate the joint influence of price and CO_2 emissions. It is found that CO_2 emissions could give customers an environmental motivation to shift loads during peak hours, as it would enable co-optimization of electricity consumption costs and carbon emissions reductions. It is also demonstrated that the consumer's preferences on the cost sub-functions of energy, inconvenience and carbon emissions affects the consumption pattern. These results are important for both the consumer and the electricity suppliers, as they illustrate the optimal decisions considered in the presence of trade-offs between multiple objectives. A further study crucial to the consumer on economic analysis of PV and battery system showed that the consumer could recoup their initial investment within 5 years of their investment.

Introduction

Demand side management (DSM) programs enable utility companies to manage the user-side electrical loads and also consumers to voluntarily lower their demand for electricity. Alternative to connecting more conventional generation to the electrical power system, DSM programs pay electrical energy users to lower their energy consumption. The utilities around the world pay for DSM capacity because it is generally economical and uncomplicated to acquire than conventional generation.[1] DSM is a set of flexible and interconnected programs that permits customers a substantial role in decreasing their general usage of electricity and shifting their load during peak times and this fosters better efficiency and operations in electrical energy systems.[2] DSM activities, which are classified into; energy response (energy efficiency and conservation (EEC)) and demand response (DR), are becoming more popular due to technological advances in smart grids and electricity market deregulation [1,2].

Energy efficiency and conservation programs entail encouraging customers to give up some of their energy usage [3–7] in order to gain some economic benefits. The energy reduction can be achieved through activities such as reducing the settings of thermostat [8,9] or retrofitting projects [10–12].

Demand response (DR) on the other hand is a highly flexible program that can be customized to the energy consumption and financial objectives of participants. DR is defined as the reduction in the consumption of electrical energy by customers from their expected consumption in response to an increase in the price of electrical energy or to incentive payments.[3,4] DR options are generally categorized as price-based and incentive-based programs [13]. It is expected that demand response will be an important stepping stone towards practical deployments of the smart grid [14]. Residential demand response (RDR) is used as an energy DSM strategy to

---

[*] Corresponding author. Tel.: +27 12 4206407; fax: +27 12 3625000.

[1] Enernoc, What is demand-side management? <http://www.enernoc.com/our-resources/term-pages/what-is-demand-side-management>.

[2] Sustainable energy regulation and policymaking for Africa, Module 14; Demand side management.< http://africa-toolkit.reeep.org/modules/Module14.pdf>.

[3] FERC, Demand Response Compensation in Organized Wholesale Energy Markets. <http://www.ferc.gov/eventcalender>.

[4] V.E. CapGemini Consulting Tech., Demand Response: A Decisive Breakthrough for Europe CapGemini Consulting Tech., 2009. <http://www.capgemini.com/insights-and-resources/by-publication//>.

http://dx.doi.org/10.1016/j.ijepes.2016.01.016
0142-0615/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

i	appliances index
t	an index of the time period
h	an index of household
k	an index of controllable appliances
A	a set of all household appliances
H	a set of all households
T	the control horizon (24 h)
K	a set of controllable appliances
Δt	sampling time (15 min)
P_i	rated power of appliance i (kW)
N_i^h	duration of appliance i being on in household h (min)
ρ_t	time of use electricity price at time t (R)
C^h	the maximum cost that household h is willing to pay (R)
d_i^h	the on-time start of appliance i in household h
e_i^h	the on-time end of appliance i in household h
$u_{i,t}^{bl,h}$	baseline commitment status of appliance i at time t in household h
$u_{i,t}^h$	optimal commitment status of the i^{th} appliance at time t
E_t^h	state of the battery at time t in household h (kW h)
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)
$P_{b,t}^h$	the battery charging power in household h (kW)
$\bar{P}_{b,t}$	the battery discharging power in household h (kW)
η_c	battery's charging efficiency
η_d	battery's discharging efficiency
DOD	depth of discharge
$P_{m,t}^h$	grid power at time t in household h (kW)
$P_{flex,t}^h$	power consumed by flexible appliances (kW)
$P_{inflex,t}^h$	power consumed by inflexible appliances (kW)
$P_{ngt,t}^h$	power consumed by night time appliances (kW)
$P_{A,t}^h$	power demanded by all appliances excluding battery at time t in household h (kW)
$P_{D,t}$	total power demanded from the grid by all at time t (kW)
P_D	the total power demanded from the grid in a day (kW)
λ_c	the carbon emission price (R/kg)
M_c^h	mass of carbon dioxide emission in household h (kg)
α_{grid}	CO_2 emission rate of the grid (kg/kW h)
w_1, w_2, w_3	sub-objective functions weighting factors
DPV	discounted present value
FV	future value of the cash flow amount (R)
r	discount or interest rate
n	time before the future cash flow occurs (yr)
AEO	annual energy output (kW h)
AEC	annual energy consumption (kW h)
AES	annual energy cost saving (R)
$Rand(R)$	South African currency ($1Rand = 0.080USD$), as at 16 Mar. 2015.

manage the peak load by use of time differentiated prices and incentive payments to control the demand[5] at household level. It has been shown that the impact of RDR is significant and most appreciable at aggregated households than individual household.[6]

The use of renewable energy sources (RES) has become inevitable in today's electrical energy system because of their sustainability and their environmental advantage. In smart grid applications, use of RES at residential level cannot be ignored as many countries including South Africa, have rolled out such systems mainly through roof-top connections. RDR models integrated with renewable energy sources is an active current global research area for smart grid applications. Electricity use in a household is mostly dependent upon the activities of the occupants and their associated use of electrical appliances [15–19], hence modeling such systems is complex. General models on household appliance scheduling without storage or renewable energy generators are presented in [20–26]. These models primarily present household appliance scheduling under demand response programs for smart grid applications. In [27,28], the scheduling problem is presented with a storage system either as a battery or plug-in hybrid electric vehicle (PHEV); the models of storage systems are also presented in [29,30]. A number of times the application of photovoltaic (PV) and battery storage is considered without appliance scheduling, hence as optimal scheduling of power supply sources of various combinations of PV/wind/diesel/battery system [31–38] on a distribution network. However, the shortfall of these models is that they are presented as a simplified problem as linear problem (LP) or mixed integer programming (MIP) problems, thereby forgoing some practical sub-functions and constraints. In our case we have considered a nonlinear inconvenience cost sub-function and nonlinear constraints such as appliance's continuous operation and the battery's exclusive operation.

South Africa has over the years implemented residential rooftop PV systems; however grid connection of small-scale renewable electricity generation is yet to be implemented because South Africa's national energy regulator (NERSA) is currently in the process of developing the regulatory framework on small-scale renewable embedded generation and the guidelines on electricity reseller tariffs.[7] Some of the challenges with small-scale renewable generation grid tie include but not limited to reverse power flows and metering tariff solutions. For this reason, in this work, we consider households with dedicated solar PV and storage systems, without infeed to the grid. Therefore the purpose of the PV is to charges the battery, which will in turn discharge during peak times to relieve the grid.

In the second part of this study we develop a model to investigate the joint influence of price and CO_2 emissions in a DR program and the motivation for this is that consumption habits may require other incentives to change rather than the proposed financial incentive. This joint influence is rarely covered by the literature. Knowledge of carbon emissions cost can incentivise investment in renewable energy at household level. By putting a price on carbon emissions, governments can save lives and protect communities from the threat of climate change.[8] In [39], the problem is presented as a multi-objective problem between two sub-functions of cost minimization through appliance scheduling and carbon emissions. The model is solved as a Markov-chain load model in order to forecast the power demands of residential consumers and a scheduling program for providing optimal schedules for smart appliances. In this paper, the problem is presented as an LP problem, as both sub-functions and constraints are linear. In [40], the thesis evaluates two formulations to schedule smart home appliances with respect to economic benefits and environmental benefits. The thesis also

---

[5] USA Department of energy <http://energy.gov/oe/technology-development/smart-grid/demand-response>.

[6] The Battle Group, Quantifying demand response benefits, Energetics, 27 January 2007 <http://sites.energetics.com/MADRI/battlegroupreport.pdf>.

[7] NERSA, response benefits, Energetics, 27 January 2007 <http://www.nersa.org.za/>.

[8] S. Blaine, SA first African country to introduce carbon emissions tax, BDLive, 28 February 2013 <http://www.bdlive.co.za/national/science/2013/02/28/>.