Applied Energy 151 (2015) 102–118

Contents lists available at ScienceDirect

Applied Energy

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

A multi-objective model for scheduling of short-term incentive-based demand response programs offered by electricity retailers

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HIGHLIGHTS

- Demand response as effective tool to shield retailers against the financial risks.
- Fast and elitist evolutionary algorithm to solve the multi-objective problem.
- Retailers aim to minimize peak demand at serving buses due to capacity charges.
- Customers change their consumption in response to financial incentives.

ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form 14 March 2015
Accepted 17 April 2015
Available online 4 May 2015

Keywords:
Electricity retail market
Evolutionary multi-objective optimization
Retailer
NSGA-II

ABSTRACT

In this paper, we formulate the electricity retailers' short-term decision-making problem in a liberalized retail market as a multi-objective optimization model. Retailers with light physical assets, such as generation and storage units in the distribution network, are considered. Following advances in smart grid technologies, electricity retailers are becoming able to employ incentive-based demand response (DR) programs in addition to their physical assets to effectively manage the risks of market price and load variations. In this model, the DR scheduling is performed simultaneously with the dispatch of generation and storage units. The ultimate goal is to find the optimal values of the hourly financial incentives offered to the end-users. The proposed model considers the capacity obligations imposed on retailers by the grid operator. The profit seeking retailer also has the objective to minimize the peak demand to avoid the high capacity charges in form of grid tariffs or penalties. The non-dominated sorting genetic algorithm II (NSGA-II) is used to solve the multi-objective problem. It is a fast and elitist multi-objective evolutionary algorithm. A case study is solved to illustrate the efficient performance of the proposed methodology. Simulation results show the effectiveness of the model for designing the incentive-based DR programs and indicate the efficiency of NSGA-II in solving the retailers' multi-objective problem.

1. Introduction

Electricity retail market liberalization starts with the unbundling of retail activities from network activities. Market liberalization guarantees the freedom of choice for electricity consumers to easily switch between the retail electricity providers. Retailers have the obligation to deliver electricity from the local utility to the end-users at a pre-specified price. The retail contracts could be with fixed tariffs for electricity consumption during the contract period or with varying retail rates. The electricity consumers protect themselves from the risk of market price changes by signing long-term contracts with the retailers. However, it is almost impossible for the retailers to completely shield themselves from the risks of the wholesale markets. They can alleviate the risk of financial losses and reduce the dependency on the wholesale market during high price periods by using their own generation and storage facilities and employing well-designed demand response (DR) programs. Deliberate changes in electricity consumption in response to new tariffs and/or financial incentives or when the network reliability is jeopardized is usually known as DR [1,2]. The DR programs are specifically implemented for the end-users equipped with smart meters. Most of the countries that are liberalizing the retail electricity markets have prepared operational plans to

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http://dx.doi.org/10.1016/j.apenergy.2015.04.067
0306-2619/

Nomenclature

Indices

t	time periods (h)
b	buses
c	end-use electricity customers
r	electricity retailers
g	DGs
s	ESSs

Variables

Payoff_r	expected payoff of retailer r in DAM (€)
d_b	electricity purchased at bus b from the wholesale market by retailer (kW)
P_g	real power output of DG unit g (kW)
u_g	binary decision variable showing the commitment status of DG unit g (1 if the unit is online and 0 otherwise)
v_g	binary decision variable for start-up status of DG unit g (1 if the unit starts up at the beginning of period t and 0 otherwise)
w_g	binary decision variable for shut-down status of DG unit g (1 if the unit shuts down at the beginning of period t and 0 otherwise)
$p_s^{\text{in/out}}$	charging/discharging power of ESS s during each time period (kW h)
E_s^{stored}	energy storage level of ESS s at the end of each time period (kW h)
x_s	binary decision variable for discharging status of ESS s (1 if it is discharging and 0 otherwise)
y_s	binary decision variable for charging status of ESS s (1 if it is charging and 0 otherwise)
m_c	binary decision variable determining the time periods that incentives should be sent to the customers (1 if the retailer should send the incentives for customer c and 0 otherwise)
FI	financial incentive for DR in DAM (€/kW h)
Δl	expected demand reduction of customer c (kW)
M_b	Peak demand at bus b

Parameters

T	scheduling horizon (number of time periods)
LMP_b	forecasted LMPs at bus b (€/kW h)
l_c	forecasted electricity consumption of consumer c (kW)
R_c	retail electricity prices offered by the retailer to consumer c for electricity consumption (€/kW h)
$(\alpha, \beta, \gamma)_g$	quadratic cost coefficients of controllable DG unit g (€/h, €/kW h, €/(kW h)^2)
c_g^{start}	start-up cost of controllable DG unit g (€)
c_g^{P}	production cost of uncontrollable DG unit g (€/kW h)
$G_g^{\text{Min/Max}}$	minimum/maximum power generation of DG unit g (kW)
$E_s^{\text{Min/Max}}$	minimum/maximum storage level of ESS s (kWh)
$\eta_s^{\text{in/out}}$	charging/discharging efficiency of ESS s
$R_s^{\text{in,Min/Max}}$	minimum/maximum charging rate of ESS s (kW/h)
$R_s^{\text{out,Min/Max}}$	minimum/maximum discharging rate of ESS s (kW/h)
$FI_c^{\text{Min/Max}}$	minimum/maximum financial incentive for consumer c (€/kW h)

Sets

Ω_r	buses that the retailer r serves loads in them
Ω_r^{b-c}	consumers served by the retailer r at bus b
$\Omega_r^{b-DG(C)}$	DG units owned by the retailer r at bus b
$\Omega_r^{b-DG(UC)}$	Uncontrollable DG units owned by the retailer r at bus b
Ω_r^{b-ESS}	ESSs owned by retailer r at bus b

roll-out smart meters, in parallel to the actions necessary for opening the market for new entrants [3]. The bidirectional communication capabilities that are provided in the context of smart grids have enabled the customers and the retailers to benefit from the real-time communication in DR programs.

Since the beginning of the electricity market deregulation, optimizing the contract portfolio has been a major problem for the electricity retailers, particularly for the new entrants of the retail market. Most of the models reported in the literature propose a single-objective problem to address the portfolio optimization problem of the profit-seeking retailers [4–8]. The retailers are usually defined as entities with no physical assets that sign the bilateral forward contracts with the GENCOs to manage the financial risks in the market. Significant changes have been observed in the structure and the operation of the retailers that participate in the liberalized electricity markets. Some of them have vertically integrated with the GENCOs or started to invest on generation and storage facilities. Furthermore, with the recent developments in the smart metering infrastructure and the home energy management systems, they can effectively apply the DR programs for the electricity end-users to manage the financial risks [9].

Several DR program schemes have been proposed in the literature, representing the DR scheduling from the viewpoint of the electricity retailers, e.g., [1,2,8,10–24]. Compared to the DR setups that can be implemented by the transmission system operators (TSO) and the distribution companies (DISCO), this problem has been less explored from the perspective of retailers. References [10,11] have developed a direct load control (DLC) program to manage the residential loads. These plans are based on an agreement between the electricity retailers and the customers to control the operation and the consumption of specific household appliances during peak demand periods and critical situations.

Alternatively to the DLC programs, the Incentive-based and price-based DR programs are implemented, which are more acceptable to the customers and the retailers in liberalized markets. These programs introduce flexibility for retail customers on a voluntary basis [8]. The customers adjust load profiles according to the varying price of electricity and the financial incentives [18]. In a price-based scheme, the retailer offers time varying rates for the electricity to the end-users. Price-based DR programs are investigated in several models to show how the retailers can benefit from them to manage the electricity consumption of the end-users [2,12–18]. For example, [16–18] have introduced the real-time pricing (RTP) approach to model the price-based DR to maximize the profit of the retailer and to reduce the peak-to-average load ratio in smart grids. Ref. [15] proposed a model for setting the price variations, which can encourage the customers to shift their loads considering time-of-use (TOU) tariffs. The hybrid market structure is considered for the retailers' DR scheduling in Refs. [13,14]. A dual price scheme is used for the customers, where some customers see the real-time prices and the rest are offered with a flat regulated pricing scheme. The incentive-based DR programs that the retailers could offer to their customers are formulated in Refs. [1,8,20,22–24]. Employing incentive-based DR programs stimulates the consumption with the rewards offered to the customers for demand reduction [25]. Refs. [1,20] have considered the uncertain behavior of customers in