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Electricity retail market model with flexible price settings and elastic price-based demand responses by consumers in distribution network

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ABSTRACT

This paper presents a novel electricity retail market model in which elastic demands of consumers in a distribution network are traded at flexible selling prices offered by a retailer. The main works of this paper are in three points: (1) Flexible and divided selling price settings over one day by the retailer, (2) flexible and elastic responses corresponding to the selling prices (price-based Demand Response: DR) by different types of consumers, and (3) distribution network physical constraints to obtain the realistic cost of tariff for usage of the distribution network imposed to the retailer are formulated. Unlike previous related works, the proposed model is a new one applicable to the behavior analysis of decision makers in the deregulated environment with such flexible transactions. In the transactions, the retailer offers a selling price for a unit time period over one day and the consumers elastically respond to the prices. Assuming that the consumers respond to the prices rationally and control their demands flexibly, we model the transaction as a Stackelberg game formulated by a bi-level programming problem. The behavior of the market players is examined in computational experiments using the spot price data in Japan Electricity Power eXchange (JEPX) and distribution network models, i.e. modified IEEE 13 bus test system model and IEEE 33-bus radial distribution test system model. We employ a genetic algorithm to find an approximated solution of the formulated non-convex bi-level programming problem. The computational results show some new findings about the deregulated retail market if flexible transactions between the retailer and the consumers are realized.

Introduction

Liberalization of electricity market is being extended all over the world and causes the newly participation of retailers in the retail market. Retailers procure the electric power from electricity markets, e.g. the day-ahead market and the future market, and resell the procured power to their clients. In order to maximize their profit, the retailers optimally determine the amount of procurement power from markets and the selling prices of the procured power [1–4]. The consumers as the clients, on the other hand, selects the retailer to contract and buy the electric power to meet their demands. To describe and analyze such complex behaviors of the decision makers theoretically, a mathematical electricity retail market model is required. In many related works, the price elasticity is usually used to model the consumer's responses to the selling prices and corresponding retailers' behaviors [2–5]. In contrast, recent development of energy management technologies such as the Home Energy Management System (HEMS) and the Building Energy Management System (BEMS) makes it possible for the consumers to flexibly and rationally control or schedule their demands elastically depending on the selling prices to reduce the electricity bills [6–12]. As taking into account such recent technological innovation for energy management, the model would be better to formulate the flexible consumers' responses to the selling prices for an appropriate retail market model. Furthermore, from the viewpoint of the deregulation of the retail market, flexible retailer's price settings corresponding to the consumers' responses should be also considered.

In this paper, we use the word "price-based DR" as consumers' demand controls by themselves depending on the selling prices. Assuming the elastic and flexible demand control at each period over one day divided into multiple small time periods, the retail market model needs to formulate the time-of-use (TOU) price settings by the retailer and corresponding the price-based DR over one day. We take into account multiple types of consumers existing in the distribution network, i.e., residential, commercial, and industrial consumers, to reflect the behavior of different types of consumers.

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Nomenclature

Sets

Ω	set of scenarios
T	set of periods $T = \{1, 2, \ldots, 48\}$
N	set of consumers $N = \{N_{re}, N_{co}, N_{in}\}$
N_{re}	set of residential consumers
N_{co}	set of commercial consumers
N_{in}	set of industrial consumers
N_{node}	set of nodes in distribution network

Indices

t	index of periods
i	index of consumers
k, l	index of nodes in distribution network

Decision variables

λ_t^{sell}	selling price at period t (¥/kWh)
P_t^{spot}	procurement power from spot market at period t (kWh)
$P_{i,t}^{+}$	surplus consumption from $P_{i,t}^{IL}$ of consumer i at period t (kWh)
$P_{i,t}^{-}$	luck consumption from $P_{i,t}^{IL}$ of consumer i at period t (kWh)

Parameters

π_ω	probability of occurrence of scenario ω
N_Ω	number of scenarios in Ω
$\lambda_{\omega,t}^{spot}$	spot price of scenario ω at period t (¥/kWh)
$\lambda_t^{spot\_ave}$	average spot price at period t of JEPX in 2013 (¥/kWh)
K^{spot}	parameter of the uncertainty of the spot price $\lambda_{\omega,t}^{spot}$
$\lambda_{\omega,t}^{RT+}$	buying price from real-time market of scenario ω at period t (¥/kWh)
$\lambda_{\omega,t}^{RT-}$	selling price to real-time market of scenario ω at period t (¥/kWh)
K^U	parameter to describe the upper λ_t^{sell}
K_{profit}	parameter to describe the upper profit of the retailer
V_{max}	upper voltage of proper range in distribution network (p.u.)
V_{min}	lower voltage of proper range in distribution network (p.u.)
$P_{i,t}^{IL}$	ideal load of consumer i at period t (kWh)
P_i^{cap}	load capacity of consumer i (kWh)
$K_{i,t}^{IL}$	the ratio of $P_{i,t}^{IL}$ against P_i^{cap}
K_i^{v}	parameter of controllable load of consumer i
$\rho_{i,t}^{dis}$	parameter of disutility due to luck of consumption against ideal load of consumer i at period t (¥/kWh)
ρ_i^{max}	maximum $\rho_{i,t}^{dis}$
G_{kl}	conductance of distribution line between node #k and #l (p.u.)
B_{kl}	susceptance of distribution line between node #k and #l (p.u.)
$P_{k,t}^{node}$	active power of consumers at node #k at period t (p.u.)
$Q_{k,t}^{node}$	reactive power of consumers at node #k at period t (p.u.)
S^{Base}	base power in the power flow equations (MVA)
V^{Base}	base voltage in the power flow equations (kV)
θ	preference of the retailer about the risk

Variables

$V_{k,t}$	magnitude of voltage at node #k at period t (p.u.)
$\phi_{k,t}$	phase of voltage at node #k at period t (rad)
$P_{i,t}$	load of consumer i at period t (kWh)
P_t^{RT+}	buying power through real-time market at period t (kWh)
P_t^{RT-}	selling power through real-time market at period t (kWh)
P_t^{loss}	line loss in distribution network at period t (kWh)
$P_{kl,t}^{loss}$	line loss at line between node #k and #l at period t (kWh)
$P_{i,t}^{c}$	uncontrollable load of consumer i at period t (kWh)
$P_{i,t}^{v}$	controllable load of consumer i at period t (kWh)
λ_{max}^{sell}	upper price of λ_t^{sell} (¥/kWh)
λ_{min}^{sell}	lower price of λ_t^{sell} (¥/kWh)
$C_{\omega,t}^{DisCo}$	network tariff at scenario ω at period t (¥)
R_i^{inb}	the ratio of the imbalance against the actual consumption of consumers
f	variables in the fractile model

The network tariff offered by electricity network operators can also affect the retailer's profit given by the trades. The retailer, who has no networks to supply the procured power to the consumers, pays the network tariff to the transmission company and the distribution company (DisCo). Thus, it is natural for an appropriate retail market model to incorporate the network tariff into the decision making problem of the retailer. Many pricing methods in the transmission and distribution networks (DN) based on congestion, line loss, and investment cost have been proposed [13–21]. Since we focus on the retail market model in DN, we ignore the an impact of transmission network and the congestion issue on the decision making of the retailer. We do not consider an impact of long-term investment planning of DisCo [21]. Note that we deal with the retailer's short-term (day-ahead) decision making problem in the retail market. Since the distribution line loss is influential for the pricing in DN [22], we deal with the cost from distribution line losses as approximated but realistic network tariff. In this paper, the network tariff offered by DisCo is calculated by solving the power flow equations. The distribution line loss in DN is obtained through the DisCo's network management problem in which the line voltage is controlled within an allowable range.

In the proposed retail market model, the retailer makes a decision assuming the rational responses of the consumers to the selling prices at periods over one day. The consumers' decisions are made with perfect information of the selling prices offered by the retailer. This type of transactions can be modeled as a Stackelberg game [1,3,23,24] and it is formulated as a bi-level programming problem. Thus, we formulate the bi-level programming problem suitable to describe the assumed retail market model.

The targeted problem in the paper, such that a determination of prices and volume of the electricity traded in the market with the clients and other market players, has been investigated by related works. A medium-term decision making approach for the retailer is presented in [3]. A framework for DisCo to minimize the operation costs using distributed generations in a distribution network considering carbon dioxide emission penalty cost is proposed in [25]. An optimal strategy for the retailer considering risk to determine forward contract portfolio is provided in [26]. Whereas the literature [26] employs the price-quota curve in each time period to describe the responses of consumers to the price, we take rational and flexible demand control by multiple types of consumers into account. The work [3] also employs the price-quota curve and focus on the risk in the medium-term trade. In the literature, the consumers do not control their demands flexibly at each time period over one day. Unlike [3,25], we focus on the transaction between the retailer and consumers with flexible TOU price