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Equilibria in the competitive retail electricity market considering uncertainty and risk management

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ABSTRACT

In a medium term planning horizon, a retailer should determine its forward contracting and pool participating strategies as well as the selling price to be offered to the customers. Considering a competitive retail electricity market, the number of clients being supplied by any retailer is a function of the selling prices and some other characteristics of all the retailers. This paper presents an equilibrium problem formulation to model the retailer's medium term decision making problem considering the strategy of other retailers. Decision making of any single retailer is formulated as a risk constraint stochastic programming problem. Uncertainty of pool prices and clients' demands is modeled with scenario generation method and CVaR (conditional value at risk) is used as the risk measure. The resulting single retailer planning problem is a quadratic constrained programming problem which is solved using the Lagrangian relaxation method and the Nash equilibrium point of the competitive retailers is achieved by successive solving of this problem for all the retailers. The performance of the proposed method is demonstrated using a realistic case study of Texas electricity market.

1. Introduction

Electricity retailers are one of the electric power market entities who purchase energy from the wholesale market and resell it to the customers [1]. Retailers purchase energy from the wholesale market by participating in the futures and the pool. On the other side, they sell energy to the customers at a fixed price during a medium-term time period [2]. Considering this planning horizon, retailer's scheduling consists of determining the optimal level of energy to be purchased in the futures and the pool and also evaluating the optimal selling price to be offered to its clients [3].

Retailer's decision-making problem is faced by a high level of uncertainty like, uncertain pool prices and uncertain client demands. A large number of methods have been proposed in the literature to model uncertain parameters in power system studies. Probabilistic methods are used to deal with the uncertainties with known PDF (probability density function). Among these methods, Monte-Carlo simulation method [4], point estimation method [5] and scenario generation method [6] are widely used in power system studies. Robust optimization method [7], interval optimization method [8] and IGDT (information gap decision theory) [9] are used when there is not enough information about the uncertain parameters. In Ref. [10] retailer's bidding strategy in the pool market is modeled as a robust optimization problem. Possiblistic (fuzzy) [11] methods are used when the uncertain parameters are described with their FMF (fuzzy membership function). Among all of these methods, stochastic programming approach based on scenario generation method has been widely used to model decision making problems under uncertainty [12]. In this method the uncertain parameters are characterized as stochastic variables and presented with a finite number of realizations called scenarios.

Retailer's planning problem is faced by the risk of profit variability because of the uncertain parameters involved in this problem. Risk management strategies proposed in the literature for this problem, can be divided into two main categories: hedging against the risk and evaluating the risk through an appropriate measure. A retailer can hedge against the risk of profit variability through signing forward contracts, employing demand response programs and using its own generation and energy storage units. The effect of forward contracts in decreasing the risk of facing with the uncertain market price is evaluated in Ref. [13]. In Refs. [14], the effect of

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Nomenclature

Set and indices

Ω	Set of scenarios.
T	Set of time periods.
F	Set of forward contracts.
N_J	Number of blocks in price quota curve.
N_T	Number of time periods.
N_Ω	Number of scenarios.
N_R	Number of retailers.
N_I	Number of blocks in forward contracting curves.

Parameters

$\lambda^{pool}_{t,\omega}$	Price of the pool market at time t and scenario ω [\$/MW].
$D_{t,\omega}$	Total system demand at time t and scenario ω [MW].
π_ω	Probability of occurrence of scenario ω.
d_t	Duration of time period t.
x^{max}_r	Retailer's maximum achievable share from total system demand related to the minimum offering price.
$\lambda^{max}_{j,r}$	Maximum allowable retailer's partial price at the *jth* part of the PQC [\$/MWh].
$\lambda^{FC}_{f,i}$	Price of the *ith* block of the forward contract f [\$/MWh].
$A_{f,t}$	Availability of forward contract f at time t.
$P^{max}_{f,i}$	Upper bound of the *ith* block of the forward contracting curve of contract f [MW].
α	Confidence level used to calculate CVaR.
τ_s	Coefficient of the *sth* characteristics related to the decision of considering the alternatives.
$V^{sw}_{i,j}$	Utility of switching to retailer j for a consumer currently provided by retailer i.
$x^{primary}_k$	Retailer's primary share from total system demand.
$\gamma_{j,r}$	Decreasing slope of the *jth* part of the PQC [\$$^{-1}$].
$Z_{k,s}$	Characteristic *sth* of retailer *kth* related to the decision of considering the alternatives.
σ_s	Coefficient of the *sth* characteristics related to the switching utility of consumers from one retailer to another.
W_k	Incentive of considering alternatives for the consumer currently provided by retailer k.
$Y_{i,j,s}$	Characteristic s of retailers related to the switching utility of consumers from one retailer to another.
$\lambda^{prime}_{k,r}$	Auxiliary variable used to calculate optimal offered price of retailer r assuming the final partial price falls into the *kth* part of the PQC [\$/MWh].

Variables

λ^{offer}_r	Retailer's offered price [\$/MWh].
$P^{FC}_{r,f,i}$	Power purchased by retailer r from the *ith* block of the forward contracting curve of contract f [MW].
$P^{Pool}_{r,t,\omega}$	Power purchased from the pool at time t and scenario ω [MW].
$R^{total}_{r,\omega}$	Total revenue of retailer r in scenario ω [\$].
$P^{demand}_{t,\omega,r}$	Total demand of the retailer r in scenario ω at time period t [MW].
x_r	Share from the total system demand of retailer r.
$P^{FC}_{r,f}$	Total power purchased from forward contract f by retailer r [MW].
$CVaR_r$	Conditional value at risk of retailer r [\$].
ζ_r	Auxiliary variable used to calculate CVaR of retailer r [\$].
$\eta_{r,\omega}$	Auxiliary variable related to scenario ω and used to calculate CVaR [\$].
$I^{total}_{r,\omega}$	Retailer's total income in scenario ω [\$].
C^{FC}_r	Total cost of forward contracts [\$].
$C^{Pool}_{r,\omega}$	Total cost of the pool in scenario ω [\$].
$\lambda^{partial}_{j,r}$	Retailers partial offering price in the *jth* part of the PQC [\$/*MWh*].
$\mu^{\eta max}_{r,\omega}$	KKT factor of the constraint related to the calculation of CVaR.
Pr^{de}_k	Probability of decision to search among alternatives for a consumer currently provided by retailer k.
$Pr^{sw}_{i,j}$	Probability of switching to retailer j for a consumer currently provided by retailer i.
$\lambda^{offer}_{k,r}$	The offered price of retailer r assuming the final partial price falling into the *kth* part of the PQC.
$\lambda^{opt}_{k,r}$	The optimum final partial price of retailer r assuming the final partial price falling into the *kth* part of the PQC.

forward contracts, call options and self-generation units has been considered in the retailer's decision making and risk management problem. In Refs. [15], retailer's optimal energy procurement strategy from bilateral contracts, self-generating units and pool market is determined using a new hybrid approach based on BICA (binary imperialist competitive algorithm) and BPSO (binary particle swarm optimization). Demand response programs can also be used by the retailers to hedge against the risk of profit variability. These programs encourage the customers to shift their demand from peak to off-peak hours. In Ref. [16] a stochastic programming approach has been proposed to determine retailer's optimal TOU (time of use) pricing strategy. In Ref. [17] an optimization model is used to determine a retailer's DA-RTP (day-ahead real time pricing) strategy. In Ref. [18] the theory of MAS (multi agent systems) is used to determine the day-ahead real time prices offered by a retailer in an agent based retail environment. A demand response simulator (DemSi) is presented in Ref. [19] to determine retailer's optimal demand response parameters considering customer's load reduction and realistic network simulation results. Retailer's risk management strategy through the incentive based demand response programs, DG (distributed generation) and ESS (energy storage systems) has been proposed in Ref. [20]. In Refs. [21], a mean-risk optimization approach is proposed for the retailer to determine its optimal power purchasing strategy from bilateral contracts, pool market and interruptible load contracts. Retailer's medium term planning problem considering the effect of interruptible load contracts is addressed in Ref. [22].

In addition to the risk hedging tools, scenario representation of uncertainties makes it possible to apply risk management in decision making problems through evaluation of an appropriate risk measure. Different risk measures such as variance [21], expected shortage [23], VaR (value at risk) [24], CVaR (conditional value at risk) [25] and etc. have been implemented to evaluate the risk level of profit variability for decision makers.

One of the important aspects of the electricity market that should be considered in the retailer's planning problem is the level of competition in the retail market. In a competitive environment, customers would have an elastic behavior in regard to the selling