Electrical Power and Energy Systems 93 (2017) 156–170

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Risk-based framework for supplying electricity from renewable generation-owning retailers to price-sensitive customers using information gap decision theory

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ARTICLE INFO

Article history:
Received 5 January 2017
Received in revised form 25 April 2017
Accepted 23 May 2017

Keywords:
Electricity retailer
Information gap decision theory
Fixed pricing
Time-of-use pricing and real-time pricing

ABSTRACT

In this paper, selling price determination problem for an electricity retailer has been studied. In the proposed model, the selling price is determined under fixed pricing (FP), time-of-use pricing (TOU) and real-time pricing (RTP). It is shown that the selling price determination based on RTP by the retailer can lead to the higher expected profit. Furthermore, to exchange power between retailer and power market, the bidding and offering curves should be prepared to bid and offer to the day-ahead market. Therefore, this paper proposes an information gap decision theory (IGDT) for obtaining of optimal bidding and offering strategies of retailer. IGDT assesses the robustness and opportunity decisions of optimal bidding and offering strategies in the presence of market price uncertainty while retailer considers whether robustness decision (risk-averse) or opportunity decision (risk-taking). It is shown that risk-aversion and risk-taker influence the expected profit and optimal bidding and offering curves. Meanwhile, the scenario-based stochastic framework is used for uncertainty modeling of market prices, client group demand and variable climate condition containing temperature, irradiation and wind speed. To validate the proposed model, three case studies are used and the results are compared.

1. Introduction

In the electricity market, determination of optimal selling price to the end-user customers by electricity retailer is necessary to maximize the expected profit [1]. Also, retailer can determine the selling price based on fixed pricing, time-of-use pricing or real-time pricing. Furthermore, the retailer should manage the uncertainty of pool market price and demand of end-user consumers. Finally, retailer should prepare the bidding and offering curves for bidding and offering to the day-ahead market to exchange power between retailer and pool market.

1.1. Literature review

The researches on retailer for determination of selling price are generally categorized into two time periods containing mid-term and short-term scheduling. The review of related researches is categorized based on objective function, type of selling price determination, solution methodology and uncertainty modeling.

Refs. [2–15] are reviewed in mid-term scheduling. The objective function of these references are minimizing cost [2,4,11–13], maximizing profit [3–10,14,15] or minimizing selling price [15]. The types of considered selling price is no pricing [2,12,13], fixed pricing [3–8,10,11,14,15] and TOU pricing [9]. Also, the solution method is based on hybrid binary imperialist competitive algorithm-binary particle swarm optimization (BICA–BPSO) [2] or GAMS optimization package [3–15]. Furthermore the uncertainty model includes Monte Carlo simulation (MCS) [3], scenario based method [4–11,15], robust optimization approach (ROA) [12,13] and information gap decision theory (IGDT) [14].

Furthermore, short-term scheduling of retailer is reviewed in [16–22]. These researches are organized similar to mid-term scheduling. The objective functions of short-term planning are maximizing profit [17–22] or minimizing cost [16,21,22]. Unlike mid-term scheduling, real-time pricing [17,21] as well as fixed pricing [19–20,22] and time-of-use pricing [18] are used as types of selling price in short-term scheduling. Also, Stackelberg game [21], genetic algorithm [16] or GAMS [17–20,22] are used to solve the problem. Furthermore, in the Refs. [16–18], the uncertainty modeling is not considered. Also, scenario based method [19–20], robust optimization approach (ROA) [21] and information gap

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http://dx.doi.org/10.1016/j.ijepes.2017.05.023
0142-0615/

Nomenclature

Index
b bilateral contract index
h the generation block index of DG units
i the minimum OFF-time and ON-time limits modeling index
j DG unit index
s Scenario index
t Time period index
z Segment index in the price-quota curve

Parameters
B number of bilateral contracts
H number of production blocks of DG units
I maximum amount of minimum OFF-time and ON-time values of DG units running from 1 to max {MUT_j, MDT_j}.
J number of DG units
S number of scenarios
T number of time periods
Z number of segments in the price-quota curve
ρ_s probability of scenario
$\lambda_{b,t}$ energy price of bilateral contracts
$P_b^{\min}, P_b^{\max}$ minimum and maximum limits of bilateral contracts
$S_{j,h}^{DG}, P_{j,h}^{MAX}$ rated block cost and power of DG units in a piecewise linear cost modeling
R_j^{down}, R_j^{up} ramp down and up rate limits of DG units
$Dn_{j,i}, Up_{j,i}$ auxiliary variable for modeling MDT and MUT constraints
$D^{offer}(l,z,t,s)$ offered energy by client group in the price-quota curve
$SP^{offer}(l,z,t)$ offered price by client group in the price-quota curve
$p_r, P_{t,s}^{wind}$ nominal and available powers of wind-turbine
$V_r, V_{ci}, V_{c0}, V_{t,s}^{w}$ rated, cut-in, cut-out and estimated wind speeds
$P_{t,s}^{PV}$ available power of PV system
$P_{Max,0}^{M}$ maximum power of PV panel at the standard condition
$G_{t,s}^{a}$ irradiation of sun
G_{a_0} irradiation of sun at the standard condition
$NOCT$ normal operating cell temperature of PV system
$T_{t,s}^{a}$ ambient temperature
$T_{M,0}$ module temperature at the standard condition
$P_{charge}^{\max}, P_{disc}^{\max}$ maximum power limit in charging and discharging modes
$X_b^{\min}, X_b^{\max}$ minimum and maximum limits of stored energy in the ESS
χ, η charging and discharging efficiencies of ESS
$\hat{\lambda}_t$ the expected market price
F_R, F_O profit target for the robustness and opportunity functions

Variables
C_B energy procurement cost from the bilateral contracts
$P_{b,t}$ energy procurement from the bilateral contracts
P_t^{BC} total energy procurement from the bilateral contracts
s_b binary variable to select the bilateral contracts
C_P energy procurement cost from pool market
λ_t actual market price
P_t^{P} energy procurement from pool market
C_{DG} energy procurement cost from DG units
$P_{j,h,t,s}^{DG}$ purchased power from DG units
$U_{j,t}^{DG}$ binary variable for on or off statues of DG units
$A(l,z,t)$ binary variable for selecting the selling price offered by retailer to the client group from the price-quota curve
$D(l,t,s)$ supplied demand to the client group by retailer
$SP(l,z,t)$ price of the interval of the price-quota curve for the client group
$R_R(l,t)$ the revenue obtained from the client group
$SP^{RTP}(l,t)$ real-time selling price by the retailer for the client group
$SP^{Fixed}(l)$ fixed selling price by the retailer for the client group
$SP_L^{TOU}(l)$ time-of-use selling price in low load level by the retailer for the client group
$SP_M^{TOU}(l)$ time-of-use selling price in medium load level by the retailer for the client group
$SP_P^{TOU}(l)$ time-of-use selling price in peak load level by the retailer for the client group
$X_{t,s}^{b}$ stored energy in the ESS
$P_{t,s}^{charge}, P_{t,s}^{disc}$ charged and discharged powers of ESS
$U_{t,s}^{charge}, U_{t,s}^{disc}$ binary variable for charging and discharging modes of ESS

Functions
$F(p,\lambda)$ profit function of retailer
$\hat{\alpha}(F_R)$ robustness function of IGDT
$\hat{\beta}(F_O)$ opportunity function of IGDT

Abbreviations
PM pool market
BCs bilateral contracts
DG distributed generation
RESs renewable energy sources
PV photovoltaic
WT wind turbine
ESS energy storage system
FP fixed pricing
TOU time-of-use pricing
RTP real-time pricing
MINLP mixed-integer non-linear programming
GAMS general algebraic modeling system

decision theory (IGDT) [22] are used as uncertainty modeling approaches.

It should be noted that optimal self-scheduling of retailer is obtained based on previous uncertainty modeling approaches. In other words, a fixed amount of power for each hour is obtained for the retailer as the optimal generation schedule. But, in the proposed paper, in order to purchase (sell) power from (to) pool market, the proposed robustness and opportunity functions of IGDT approach are used to create the bidding and offering curves which are used to purchase and sell power, respectively. In other words, the power-price pairs (curves) are obtained from the proposed method which is not considered in the previous works.

1.2. Procedure and contributions

In this paper, the expected profit function of retailer is maximized. In the proposed model, the pool market, bilateral contracts and DG units plus the renewable energy sources containing wind turbine, PV system as well as ESS are used as alternative energy sources. Also, the selling price by retailer is determined in three cases including fixed pricing, time-of-use pricing and real-time pricing and compared with each other. Furthermore, the scenario-based stochastic framework is used for uncertainty modeling of demand of end-user, wind speed, irradiation and temperature. Finally, the pool market price uncertainty implies that the