Sādhanā (2022)47:37
https://doi.org/10.1007/s12046-021-01800-3

Risk-based performance of regional-market management considering information gap decision theory and demand response program

MOJTABA NAJAFI[1,*], SEYYED EBRAHIM HOSSEINI[1] and ALI AKHAVEIN[2]

[1]Department of Electrical Engineering, Bushehr Branch, Islamic Azad University, Bushehr, Iran
[2]Faculty of Electrical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran
e-mail: mnajafi@iaubushehr.ac.ir

MS received 21 October 2020; revised 6 December 2021; accepted 17 December 2021

Abstract. In the current study, the optimal performance of regional market management (RMM) is presented in one specific area of the market in order to determine the optimal demand aiming to minimize the costs of smoothing the load curve, and to implement the demand response program (DRP). In addition, the attempt has been made in this study to minimize the involuntary lost energy in terms of the initial price uncertainty and the technical constraints including the price fluctuation limits, demand ceilings and the relative risk limits. Furthermore, a market-based tensile model is presented in the form of a combination of the formulations of over lapping generations (OLG) and price elasticity (PEM) for determining demand levels in DRP. The information-gap decision theory (IGDT) is presented to model the initial price uncertainty in the above issue, according to different rates of time preference as well as the algorithm of the co-evolutionary particle swarm optimization (C-PSO). IGDT risk-aversion and risk-taking strategies help RMM to select the best strategy with the desired risk level for controlling the price uncertainty, improving the load curve, enhancing the reliability and reducing the costs.

Keywords. Regional market management; demand response program; diamond's OLG model; uncertainty; information-gap decision theory.

1. Introduction

In recent years, many studies have been conducted on the price and demand determination in DRPs based on definite, random, and uncertainty models, among which uncertainty models become more prominent [1–6].

The significant contributions of this study are as follows:

(1) Modeling TOU program by using the combined Diamond's OLG and PE models.
(2) Combining the problem of optimizing the load curve smoothing, reducing the cost of TOU and the unintentional lost energy to determine the optimal amount of price and demand in terms of technical limitations such as price fluctuation limit, demand ceiling and relative risk limit.
(3) Robust strategy of the proposed system operation obtained from the robustness function of the IGDT approach,
(4) Opportunistic strategy of the proposed system operation obtained from the opportunity function of the IGDT approach.

2. Formulation of the definite model of the problem

The objective function and the problem constraints considered in this section are explained from the RMM viewpoints.

*For correspondence
Published online: 15 February 2022

2.1 *Objective function*

The overall objective function of an optimization problem for determining the demand in such a way that the cost of RMM is minimized throughout the distribution period is in the following equation:

$$C(d,p) = MIN\left[\underbrace{\sum_{t=1}^{24}\left(\left(\rho^0(t)\times d^0(t)\right)-\left(\rho(t)\times d(t)\right)\right)}_{1} + \underbrace{\sum_{t=1}^{24}\left(VOLL(t)\times ENS(t)\right)}_{2} + \underbrace{\rho^0\times\left(\max(d)-\min(d)\right)}_{3}\right] \quad \forall d\in\varphi_d \tag{1}$$

In Equation (1), the first, the second and the third parts are the cost of implementing TOU, the cost of involuntary energy loss, and the cost of smoothing the load curve, respectively. In Equation (1), the cost of TOU implementation, the cost of involuntary energy lost, the cost of smoothing the load curve and the cost of electricity purchased from upstream are indicated in the first to the fourth parts, respectively. The first part is determined according to the reference [7]. More specifically, the third part refers to this concept that is based on the RMM's point of view: the smoother the load curve, the better the performance of the system. One of the parameters for measuring the load curve smoothness is the difference between the maximum and minimum load curve characteristics, meaning that the smaller the difference, the smoother the load curve. Therefore, minimizing it is one of the objectives of RMM. To calculate the price of electricity in different periods after the TOU program, the parameter δ is used. In other words, one of the main objectives of Equation (1) is to determine the optimal amount of this parameter.

$$\rho = \begin{bmatrix}\rho_{peak}\\ \rho_{flat}\\ \rho_{off-peak}\end{bmatrix} = \begin{bmatrix}\rho^0+\delta\\ \rho^0\\ \rho^0-\delta\end{bmatrix} \tag{2}$$

Increasing the amount of δ results in the increase of ρ_{peak} and the decrease of $\rho_{off-peak}$. This method will continue as long as the objective function in the equation (1) has the lowest possible value, and then the optimal value of δ and the electricity price after TOU program will be determined. In fact, this method allows customers to change their consumption pattern to reduce their consumption during the peak period or to transfer it to flat or off-peak periods (figures 1, 2, 3 and 4).

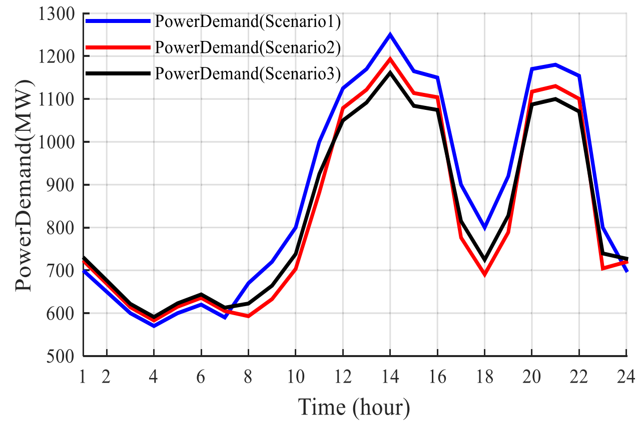

Figure 1. Daily power demand curve result of the Case 1.

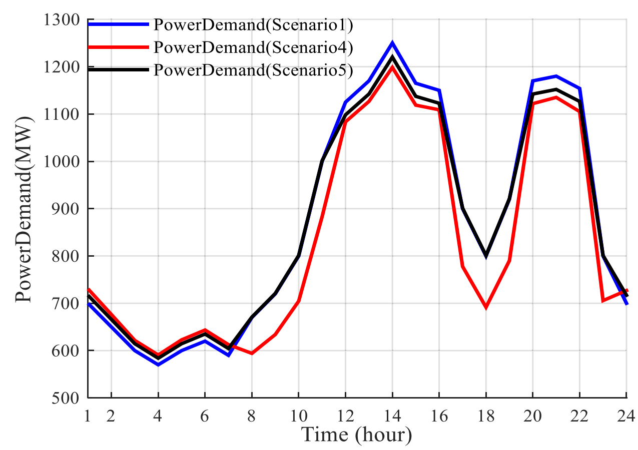

Figure 2. Daily power demand curve result of the Case 2.

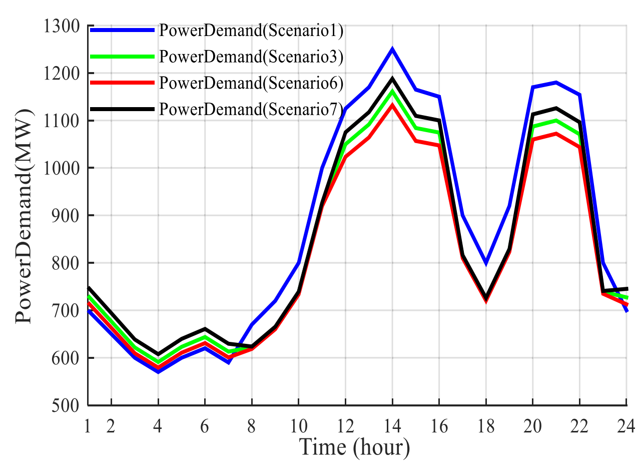

Figure 3. Daily power demand curve result of the Case 3.

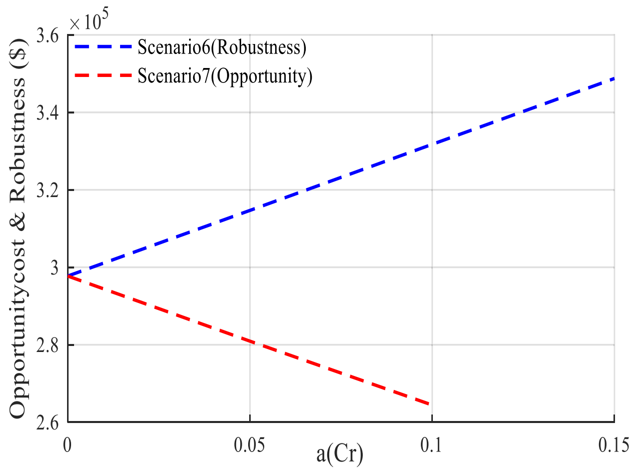

Figure 4. Effect robust & opportunity functions of cost RMM.

2.2 *Constraints*

(A) Relative risk limit: This restriction is defined based on the coefficient that has the following range:

$$\theta_{\min} \leq \theta \leq \theta_{\max} \tag{3}$$

$\theta_{\min}$ and $\theta_{\max}$ it is usually considered 0.2 and 0.9, respectively.

(B) Price fluctuation limit: The limit of price changes in different periods of δ is defined based on the following range:

$$\delta_{\min} \leq \delta \leq \delta_{\max} \tag{4}$$

In reference [7], $\delta_{\min}$ and $\delta_{\max}$ are considered to be 0.25 and 25, respectively, per $/MWh.

(C) Demand ceiling: It is assumed that consumer demand has the following range:

$$\min\left(d^0\right) \leq d(t) \leq \max\left(d^0\right) \quad \forall t \in \varphi_{peak}, \varphi_{flat}, \varphi_{off-peak} \tag{5}$$

(D) Power purchased: It is assumed that the power purchased by the RMM has the following range

$$P_{grid}^{\min} \leq P_{grid}(t) \leq P_{grid}^{\max} \tag{6}$$

(E) Power balance constraint:

$$\sum_{t=1}^{24} P_{grid}(t) = d(t) + P_L(t) \tag{7}$$

$$P_L(t) = \sum_{t=1}^{24} B_0 \times P_{grid}(t) \tag{8}$$

2.3 *Energy of involuntary lost formulation*

The TOU program leads to the improvement of the reliability in the regional electricity market. Here, the cost of involuntary energy losses is selected as one of the objectives of RMM, which is defined below.

$$\begin{cases} \text{Cost of involuntary energy loss} = ENS(t) \times VOLL(t) \\ ENS(t) = d(t) \times A \qquad {\scriptstyle(\$)} \qquad A = \lambda \times r \end{cases} \tag{9}$$

2.4 *Suggested model for TOU*

In the current study, it is assumed that the RMM uses the TOU program to smooth the load curve. Furthermore, Diamond's OLG model is used to model subscribers shift loading while logarithmic and PEM models are used to model subscribers load removal. The reason for choosing a logarithmic model is that some studies showed that this

Table 1. Classification of the recent studies conducted in the field of DRPs.

			Uncertainty parameters DRP			
Ref. no.	DRP Model	DRP	Load	Price	Uncertainty model	Reliability index
[1, 2]	PE matrix	IBP	NO	NO	NO	NO
[3]	PE matrix	TBP	Yes	No	Stochastic	NO
[4]	NO	IBP	NO	Yes	Evidence uncertainty	NO
[5]	NO	IBP	Yes	NO	IGDT uncertainty	VOLL
[6]	Diamond's OLG	EDRP	NO	NO	NO	NO
Proposed method	PE & diamond's OLG	TOU	NO	Yes	IGDT uncertainty	Involuntary Energy Loss

* *IBP* Incentive-based programs

* *TBP* Time-based programs

model has almost more conservative responses than the other models, the values of which are in the middle of the values of other models.

3. The process of implementing the proposed method

The definite model of the proposed problem is comprised of equations (1)–(9) in which the objective function is obtained by determining the optimal value of price and demand in terms of the above constraints. Given that the price is an uncertain parameter, IGDT is used to address this issue. This method uses the opportunity and robustness functions to determine the risk-aversion and the risk-seeking of the proposed problem. This means that after determining the value of the objective function of definite model of the proposed problem, the minimum and maximum ranges of the value that the objective function is allowed to change is determined by the opportunity and robustness functions, respectively. The IGDT consists of three parts: the system model, the operating requirements, and the uncertainty modeling (tables 1, 2, 3).

4. Results and discussions

In this section, the results regarding TOU program evaluations are investigated with the aim of minimizing the cost of RMM by the use of the C-PSO algorithm. In order to

Table 2. Initial demand of the customers.

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Demand (MW)	700	650	600	570	600	620	590	670	720	800	1000	1125
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Demand (MW)	1170	1250	1165	1150	900	800	920	1170	1180	1154	800	700

Table 3. Parameters of different scenarios [7, 30].

$E_{offpeak}$	E_{flat}	E_{peak}	ρ_1	ρ_2	VOLT (t) $/ (MWh)	λ (Failure/Year)	r (year)
+0.2	+0.2	+0.2	0.3	0.425	1.5	0.006	5.3

Table 4. Studied scenarios.

Scenario	Case study	Uncertainty model	Rate of time preference	PE rate	DRP
1	Base case	No	No	No	No
2	First	No	$\rho_1 = 0.6, \rho_2 = 0.8$	E	TOU
3		No	$\rho_1 = 0.4, \rho_2 = 0.6$	E	TOU
4	Second	No	$\rho_1 = 0.4, \rho_2 = 0.6$	No	TOU(18)
5		No	No	E	TOU(30)
6	Third	IGDT (Robustness)	$\rho_1 = 0.4, \rho_2 = 0.6$	E	TOU
7		IGDT (Opportunity)	$\rho_1 = 0.4, \rho_2 = 0.6$	E	TOU

Table 5. Effects of implementing DR in different scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
$\rho_{OffPeak}$($/Mwh)	14	12.8349	12.9036	12.9615	13.25	14.7815	11.9826
ρ_{flat}($/Mwh)	14	14	14	14	14	15.4	13.3
ρ_{Peak}($/Mwh)	14	15.1651	15.0964	15.0385	14.75	16.0185	14.6174
Optimal δ ($/Mwh)	0	1.1651	1.0964	1.0385	0.75	0.6185	1.3174
Optimal θ	–	0.3937	0.3173	0.3957	–	0.3517	0.2988
Optimal α	0	0	0	0	0	0.15	0.1
Peak Reduction (MW)	0	56.8561	88.7697	51.6395	29.6914	118.3181	62.0313
Total cost RMM ($)	353505.85	298481.55	297742.95	298163.73	355434.53	348749.28	264436.80

describe the performance of the proposed method, three case studies have been conducted in the current study according to Table 4. In this regard, case study 1 is related to different values of the rates of time preference in TOU program considering scenarios 2 and 3, and case study 2 is the implementation of the proposed model according to the TOU considering scenarios 4 and 5. In addition, case study 3 is the investigation of the price uncertainty in the presence of the TOU program according to the IGDT model considering scenarios 6 and 7. Furthermore, Scenario 1 indicates the basic mode without implementing the TOU program.

5. Conclusion

In this study, at first, the definite model of the proposed problem was presented with the aim of smoothing the load curve, reducing TOU costs and involuntary energy loss by determining the optimal value of price and demand considering some technical limitations including the price fluctuation limit, the demand ceiling and the relative risk limit (Table 5). Furthermore, in order to determine the amount of customer demand in TOU, a flexible model was provided based on the combination of Diamond's OLG and PE models that was more efficient in modeling the customer behavior. Then, due to the uncertainty of the price of electricity, the uncertainty model (IGDT) of the proposed problem was presented. The positive aspect of uncertainty is represented by modeling the IGDT opportunity function and the negative aspect of uncertainty is presented by modeling the IGDT robustness function. Using various strategies, the RMM attempts to eliminate the price uncertainty.

List of symbols

Sets and index

t	Index of time
φ_{peak},φ_{flat},$\varphi_{off\text{-}peak}$ and φ_d	Sets of peak load time, flat load time, off-peak loadtime and load

Constants

$\rho^0(t)$	Initial energy price at time t (\$/MWh)
ρ^0	Initial energy price (\$/MWh)
$d^0(t)$	Initial demand at time t (MWh)
d^0	Initial demand (MW)
λ	failure rate(Failure/year)
r	Average outage time (year)
δ_{min},δ_{max}	Minimum and maximum value of Price fluctuationlimit
θ_{min},θ_{max}	Minimum and maximum value of relative risk aversion
$P^{\min}_{grid}, P^{\max}_{grid}$	Minimum and maximum value of power purchased from the main grid
$\pi(t)$	Price purchased from the main grid at time t (MW)
B_0	Loss coefficient parameter
$\rho_1,\ \rho_2$	Rate of time preference after the implementation of DRP
$d^0_{peak}, d^0_{flat} d^0_{off-peak}$	Energy consumption before implementing DRP during the peak, flat and off-peak hours (MWh)
E_{peak}, E_{flat} $E_{off-peak}$	Price Elasticity Matrix in the peak, flat and offpeakhours
$d^0_{peak}(t), d^0_{flat}(t) d^0_{off-peak}(t)$	Energy consumption before implementing DRP attime t during the peak, flat and off-peak hours(MWh)
$\tilde{p}_0(t)$	Forecasted uncertainty variable at time t
C_b	Minimum expected cost of RMM
C_r	Critical cost for robustness function
C_o	Critical cost for opportunity function
μ	Percentage increase in cost for RMM
γ	Percentage decrease in cost for RMM

Variables

ρ_{peak}, ρ_{flat} $\rho_{off-peak}$	Electricity price during the peak, flat and off-peak hours (\$/MWh)
$\rho(t)$	Electricity price after implementing DRP at time t (\$/MWh)
$d(t)$	Demand after implementing DRP at time t (MWh)
d	Demand after implementing DRP (MW)
θ	Relative risk aversion
$ENS(t)$	Energy not supplied at time t (MWh)
$VOLL(t)$	Value of the lost load at time t (\$/MWh)
A	Annual outage
Utility	Utility function
$d_{peak}, d_{flat} d_{off-peak}$	Energy consumption after implementing DRP during the peak, flat and off-peak hours (MWh)
$P_{\mathrm{grid}}(t)$	Power purchased from the main grid at time t (MW)

$P_{L(\mathrm{t})}$	Power transmission loss at time t (MWh)
$B^{/}$	Budget after the implementation of the DRP
ζ	Lagrange multiplier
ℓ	Lagrange function
$\bar{\bar{d}}_{peak}, \bar{\bar{d}}_{flat}$ $\bar{\bar{d}}_{off-peak}$	Load reduction after implementing DRP duringthe peak, flat and off-peak hours (MWh)
α	uncertainty radius
$\bar{p}_0(t)$	Actual uncertainty variable at time t

Functions

$C(d, p)$	Total cost function of RMM per $
$\hat{\alpha}(C_r)$	Robustness function
$\hat{\beta}(C_o)$	Opportunity function

References

[1] Yu D, Xu X, Dong M, Nojavan S, Jermsittiparsert K, Abdollahi A and Pashaei-Didani H 2020 Modeling and prioritizing dynamic demand response programs in the electricity markets. *Sustain. Cities Soc.* 53: 101921

[2] Imani M H, Ghadi M J, Ghavidel S and Li L 2018 Demand response modeling in microgrid operation: a review and application for incentive-based and time-based programs. *Renew. Sustain. Energy Rev.* 94: 486–499

[3] Li K, Liu L, Wang F, Wang T, Duić N, Shafie-khah M and Catalão J P 2019 Impact factors analysis on the probability characterized effects of time of use demand response tariffs using association rule mining method. *Energy Convers. Manag.* 197: 111891

[4] Liu W, Huang Y, Li Z, Yang Y and Yi F 2020 Optimal allocation for coupling device in an integrated energy system considering complex uncertainties of demand response. *Energy*, 198: 117279

[5] Nourollahi R, Nojavan S and Zare K 2020 Risk-Based Purchasing Energy for Electricity Consumers by Retailer Using Information Gap Decision Theory Considering Demand Response Exchange. *Electr. Markets*, pp. 135–168

[6] Sharifi R, Anvari-Moghaddam A, Fathi S H, Guerrero J M and Vahidinasab V 2019 An optimal market-oriented demand response model for price-responsive residential consumers. *Energy Efficiency* 12(3): 803–815

[7] Nwulu N I and Xia X 2015 Multi-objective dynamic economic emission dispatch of electric power generation integrated with game theory based demand response programs. *Energy Convers. Manag.* 89: 963–974