Electrical Power and Energy Systems 33 (2011) 1125–1132

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A demand response based solution for LMP management in power markets

Rahmat Aazami [a], Kaveh Aflaki [b], Mahmoud Reza Haghifam [a,*]

[a] Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran
[b] Electrical and Computer Engineering Department, Illinois Institute of Technology, Chicago, IL 60616 USA

ARTICLE INFO

Article history:
Received 21 May 2009
Received in revised form 2 November 2010
Accepted 9 December 2010
Available online 22 February 2011

Keywords:
Restructured power systems
Demand response (DR)
Emergency demand response program (EDRP)
Local marginal pricing (LMP)

ABSTRACT

In recent years, most of the countries around the world have gone through the power system restructuring process. Along with this restructuring in power market there are some issues like LMP problems that need to be solved base on demand response. In this article, demand-side management (DSM) programs have been effective to address LMPs in the market and system operators experience throughout their day-to-day activities. In particularly, these programs can help independent system operator (ISO) to reduce price volatility during peak demand hours. For achieving this purpose, a multi-objective optimal power flow is proposed to study the impact of a model for a demand response program on price spikes. Actually a new framework using demand response program was presented for price spikes reduction. As a case study for the formulation, the IEEE 9-bus, load curve of Mid-Atlantic region of the New York network is used to compare local prices in the system with and without emergency demand response program (EDRP). The study results demonstrate the effectiveness of these programs in an electricity market and showing them as appropriate tools in managing the LMPs of the power market more efficiently.

1. Introduction

RESTRUCTURING and privatization of assets, when managed properly in conformance with sound socioeconomic principles pertaining to specific cultures across the globe, could lead to better services, technological improvements, improved reliability, and the reduction in customer costs [1]. Independent system operator in restructured power system tries to control reliability and security of the system while maximizing social welfare. To have reliable grid not only having enough generation reserve in system can help the system, but also having demand response on the other hand can lead to controlling LMPs.

Consequently, in addition to supply offers, participation of customers in electricity market increase the competitiveness overall. In response to price volatility, customers would normally modify their demand, which results in smaller price spikes, i.e. some customers can response to price spikes and hence shift their demand to cheaper hours [2].

Demand Response (DR) is defined as the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. DR is divided into two basic groups and several subgroups:

A: Incentive-based programs:

(A-1) Direct load control.
(A-2) Interruptible/curtail able service.
(A-3) Demand bidding/buy back.
(A-4) Emergency demand response program (EDRP).
(A-5) Capacity market program.
(A-6) Ancillary service markets.

B: Time-based programs:

(B-1) Time-of-use program.
(B-2) Real time pricing program.
(B-3) Critical peak pricing program.

The benefits of DR include increased static and dynamic efficiency, better capacity utilization, pricing patterns that better reflect actual costs, reduction of price spikes, decentralized mitigation of market power, and improved risk management [3,4]. EDRP is a DR program that provides incentives for customers to reduce loads during power system emergency states; however the curtailment is voluntary and no penalty applies if customers choose not to curtail, also the rates are fixed pre-specified and no capacity payments are paid [5]. Some of the EDRP currently used in electricity markets can be found with details in [6]. Bulk power system operators primarily rely on adjustments in generator's MW output to maintain system reliability [7]. In principle, changes in

* Corresponding author. Address. P. O. Box 14115-111, Tehran, Iran. Tel.: +98 91 2185 2141; fax: +98 21 8800 6544.

E-mail addresses: r.azami@modares.ac.ir (R. Aazami), kaflakik@iit.edu (K. Aflaki), haghifam@modares.ac.ir (M.R. Haghifam).

0142-0615/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijepes.2010.12.018

Nomenclature

Indices

E	elasticity of the demand
q	the demand value (MWh)
ρ	electricity energy price ($/MWh)
ρ_0	initial electricity energy price ($/MWh)
q_0	initial demand value (MWh)
i,j	indexes for bus

Variables

$\Delta d(t_i)$	demand changes in time interval t_i
$\Delta\rho(t_i)$	price changes in interval t_i
$\Delta\rho(t_j)$	price changes in time interval t_j
$d(i)$	customer demand in ith hour after EDRP
$d_0(i)$	customer demand in ith hour before EDRP
$\rho(i)$	electricity price in ith hour after EDRP
$\rho_0(i)$	electricity price in ith hour before EDRP
$EDLC$	incentive value in ith hour ($/MWh)
$E(i)$	self elasticity of the demand in ith hour
$E(i,j)$	cross elasticity of the demand between i and jth hours
$C_i(P_{gi})$	cost function for generator i
P_{gi}	active power produced by generator i
P_{di}	active power consumed by demand i
Q_{gi}	reactive power produced by generator i
Q_{di}	reactive power consumed by demand i
V_i	voltage magnitude in bus i
$V_i^{\min}$	minimum voltage magnitude in bus i
$V_i^{\max}$	maximum voltage magnitude in bus i
δ_i	phase angle in bus i
$\delta_i^{\min}$	minimum phase angle in bus i
$\delta_i^{\max}$	maximum phase angle in bus i
$P_{gi}^{\min}$	minimum active power output of generator i
$P_{gi}^{\max}$	maximum active power output of generator i
$Q_{gi}^{\min}$	minimum reactive active power output of generator i
$Q_{gi}^{\max}$	maximum reactive active power output of generator i
S_{ij}	power flow in line i–j
$S_{ij}^{\max}$	maximum power flow in line i–j
$L(P_i, Q_i)$	Lagrange function
LMP_i	local marginal prices of real powers at bus i
$C_i(P_{EDRPi})$	EDRP cost for ISO
P_{EDRPi}	EDRP power values in bus i
Q_{EDRPi}	EDRP power values in bus i
$P_{EDRPi}^{\min}$	minimum EDRP active power value
$Q_{EDRP}^{\min}$	minimum EDRP reactive power value

electricity demand could serve as generator movements in meeting the reliability requirements [8]. So, customer loads could be able to participate in these markets. The participation of these resources will enhance reliability and lower costs of maintaining reliability for all customers hence saving money for participating customers. At peak hours in which the demand is high, the electric prices are normally high. For a contingency in power system or a sudden demand increase of these hours, the electric prices would increase quickly. Therefore in these conditions, by means of EDRP, consumers could act as new sources. These new sources, hence benefiting by both ISO and customers reducing system cost to as well as maintaining reliability [9,10]. Moreover, to improve power system security, load management can be implemented [11].

In this paper, in Section 2, an EDRP model is presented. The effect of incorporation of the EDRP model into an electricity market price is discussed in Section 3. Sections 4 and 5 are case study for numerical results and conclusion respectively of this research.

2. Demand response economic model

Before deregulation, most consumers were non-dispatch-able loads and did not have effective participation in power system operation and dispatch process. Therefore, they were not able to response to the prices effectively. A significant portion of those loads have been turned into dis-loads as a result of deregulation. Fig. 1 shows how the demand elasticity could affect both electricity prices and demand [12–14].

The Elasticity shown below is defined as a ratio of the relative change in demand to the relative change in prices.

$$E = \frac{\partial q}{\partial \rho} = \frac{\rho_0}{q_0} \cdot \frac{dq}{dp} \tag{1}$$

Self elasticity (ξ_{ii}) and cross elasticity (ξ_{ij}) can be written as:

$$\xi_{ii} = \frac{\Delta d(t_i)/d_0}{\Delta\rho(t_i)/\rho_0} \qquad \xi_{ij} = \frac{\Delta d(t_i)/d_0}{\Delta\rho(t_j)/\rho_0} \tag{2}$$

Self elasticity and cross elasticity are negative and positive values, respectively. If the relative change in demand is larger than the relative change in price, the demand is said to be elastic. On the other hand, if the relative change in demand is smaller than the relative change in price, the demand said to be inelastic. So the elasticity coefficients for hours of a day can be arranged in a 24 by 24 matrix E. The detailed process of modeling and formulating how an EDRP program affects the electricity demand and how the maximum benefit of customers is achieved have been discussed in [15]. Thus, the corresponding responsive economic model of the load is presented by:

$$d(i) = \left\{ \begin{array}{l} d_0(i) + \sum_{j=1}^{24} E_0(i,j) \cdot \frac{d_0(i)}{\rho_0(j)} \times \\ A(j) + \frac{E(i)[\rho(i) - \rho_0(i) + A(i)]}{\rho_0(i)} \end{array} \right\} \quad i = 1, 2, \ldots, 24 \tag{3}$$

Detail of demand response economic model and impact on the electricity demand, which is based on maximizing the benefit of customers and social welfare, is presented in [15] that can be used for more explanation. Eq. (3) shows how much the customers demand should be in order to achieve maximum benefit in a 24-h interval. This model also includes the impact of time-of-use pricing which is not discussed in this work. Therefore, the following model is deployed instead:

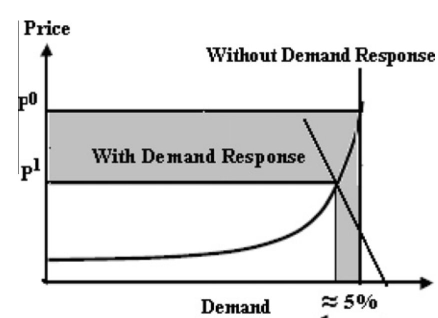

Fig. 1. Effect of demand variation on the electric energy price [11].

$$d(i) = \left\{ d_0(i) + \sum_{j=14}^{18} E_0(i,j) \cdot \frac{d_0(i)}{\rho_0(j)} \times A(j) \right\} \tag{4}$$

In Eq. (4) i = EDRP Non Event Hours.

$$d(i) = \left\{ \begin{matrix} d_0(i) + \sum_{j=14}^{18} E_0(i,j) \cdot \frac{d_0(i)}{\rho_0(j)} \times \\ A(j) + \frac{E(i) \times A(i)}{\rho_0(i)} \end{matrix} \right\} \tag{5}$$

In Eq. (5) i = EDRP Event Hours.

3. New formulation for LMP calculating with EDRP in normal and emergency sates

Local marginal pricing (LMP), which is based on the short run marginal cost of supplying energy, was developed in the 1980s and has grown to be the dominant method of pricing energy in electricity markets. The use of LMPs has grown because the physical constraints of the system and economic realities are accurately represented. For instance [16,17] utilized LMP for real-time control of power system and optimum placement of distributed generations. Local marginal prices (LMPs) are the Lagrangian multipliers associated with power flow equations in an optimal power flow problem, The Lagrangian multiplier values are calculated by solving the first-order necessary condition of Lagrangian, partial derivatives of the Lagrangian with respect to every variable concerned.

Mathematically, the normal dispatch problem with a cost minimization can be written as:

$$Min \sum_{i \in n_g} (C_i(P_{gi})) = \sum_{i \in n_g} \left(a_{gi} + b_{gi} P_{gi} + c_{gi} P_{gi}^2 \right) \tag{6}$$

3.1. Equality constrains

Power flow equations corresponding to both real and reactive power balance equations as load flow constraints can be written for all the buses as:

$$\begin{aligned} &P_i = P_{gi} - P_{di} = \sum_{j=1}^{N_b} V_i V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] \\ &\forall i = 1, \ldots, N_b \\ &Q_i = Q_{gi} - Q_{di} = \sum_{j=1}^{N_b} V_i V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] \\ &\forall i = 1, \ldots, N_b \end{aligned} \tag{7}$$

System real and reactive power balance equations can be written as:

$$\begin{aligned} Ploss &= \sum_{i \in N_b} P_{gi} - \sum_{i \in N_b} P_{di} \\ &= \sum_{i=1}^{N_b} \sum_{j=1}^{N_b} \left\{ \begin{matrix} \frac{R_{ij}}{V_i V_j} [P_i P_j \cos(\delta_i - \delta_j) + Q_i Q_j \cos(\delta_i - \delta_j) - \\ P_i Q_j \sin(\delta_i - \delta_j) + P_j Q_i \sin(\delta_i - \delta_j)] \end{matrix} \right\} \end{aligned} \tag{8}$$

$$\begin{aligned} Qloss &= \sum_{i \in N_b} Q_{gi} - \sum_{i \in N_b} Q_{di} \\ &= \sum_{i=1}^{N_b} \sum_{j=1}^{N_b} \left\{ \begin{matrix} \frac{R_{ij}}{V_i V_j} [P_j Q_i \cos(\delta_i - \delta_j) - P_i P_j \sin(\delta_i - \delta_j) - \\ Q_i Q_j \sin(\delta_i - \delta_j) - P_i Q_j \cos(\delta_i - \delta_j)] \end{matrix} \right\} \end{aligned} \tag{9}$$

3.2. Inequality constrains

Real power generation limit includes the upper and lower real power generation limits of generators at bus i:

$$P_{gi}^{\min} \leqslant P_{gi} \leqslant P_{gi}^{\max} \tag{10}$$

Reactive power generation limit includes the upper and lower reactive power generation limits of generators and other reactive sources at bus i:

$$Q_{gi}^{\min} \leqslant Q_{gi} \leqslant Q_{gi}^{\max} \tag{11}$$

Voltage limit includes the upper and lower voltage magnitude limits at bus i:

$$V_i^{\min} \leqslant V_i \leqslant V_i^{\max} \tag{12}$$

Phase angle limit includes the upper and lower angle limits at bus i:

$$\delta_i^{\min} \leqslant \delta_i \leqslant \delta_i^{\max} \tag{13}$$

Line flow limits constraints represent maximum power flow in a transmission line and are based on thermal and stability considerations. S_{ij} is MVA line flows from bus i to bus j. The line flow limit can be written as:

$$S_{ij} \leqslant S_{ij}^{\max} \tag{14}$$

The Lagrangian function for the local marginal price determination can be written as a function of P_i and Q_i as:

$$\begin{aligned} L(P_i, Q_i) = &\sum_{i \in n_g} (C_i(P_{gi})) + \sum_{i \in N_b} (LMP_{pi}) \\ &\times \left[P_i - \sum_{j=1}^{N_b} V_i V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] \right] \\ &+ \sum_{i \in N_b} (LMP_{qi}) \times \left[Q_i - \sum_{j=1}^{N_b} V_i V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] \right] \\ &+ \beta_{Ploss} \left(\sum_{i \in N_b} P_{gi} - \sum_{i \in N_b} P_{di} - \sum_{i=1}^{N_b} \sum_{j=1}^{N_b} \left\{ \frac{R_{ij}}{V_i V_j} [P_i P_j \cos(\delta_i - \delta_j) \right. \right. \\ &\left. \left. + Q_i Q_j \cos(\delta_i - \delta_j) - P_i Q_j \sin(\delta_i - \delta_j) + P_j Q_i \sin(\delta_i - \delta_j)] \right\} \right) \\ &+ \beta_{Qloss} \left\{ \sum_{i \in N_b} Q_{gi} - \sum_{i \in N_b} Q_{di} - \sum_{i=1}^{N_b} \sum_{j=1}^{N_b} \left\{ \frac{R_{ij}}{V_i V_j} [P_j Q_i \cos(\delta_i - \delta_j) \right. \right. \\ &\left. \left. - P_i P_j \sin(\delta_i - \delta_j) - Q_i Q_j \sin(\delta_i - \delta_j) - P_i Q_j \cos(\delta_i - \delta_j)] \right\} \right\} \\ &+ \sum_{i=1}^{N_g} \omega_i^{\max} (P_i^{\max} - P_i) + \sum_{i=1}^{N_g} \omega_i^{\min} \left(P_i - P_i^{\min} \right) \\ &+ \sum_{i=1}^{N_g} \sigma_i^{\max} (Q_i^{\max} - Q_i) + \sum_{i=1}^{N_g} \sigma_i^{\min} \left(Q_i - Q_i^{\min} \right) \\ &+ \sum_{i=1}^{N_b} v_i^{\max} (V_i^{\max} - V_i) + \sum_{i=1}^{N_b} v_i^{\min} \left(V_i - V_i^{\min} \right) \\ &+ \sum_{i=1}^{N_b} \gamma_i^{\max} (\delta_i^{\max} - \delta_i) + \sum_{i=1}^{N_b} \gamma_i^{\min} \left(\delta_i - \delta_i^{\min} \right) \\ &+ \sum_{ij=1}^{N_l} \alpha_{ij}^{\max} \left(S_{ij}^{\max} - S_{ij} \right) \end{aligned} \tag{15}$$

Knowing Lagrangian function, real local marginal price at any bus i can be determined as the partial derivative of the Lagrangian function with respect to injected real power equated to zero as:

$$\begin{aligned} LMP_i = &\frac{\partial L(P_i, Q_i)}{\partial P_i} = 0 \Rightarrow LMP_i \\ &= \frac{\partial \left(\sum_{i \in n_g} (C_i(P_{gi})) \right)}{\partial P_i} + \omega_i^{\max} - \omega_i^{\min} + \beta_{Ploss} \left(1 - \frac{\partial Ploss}{\partial P_i} \right) \\ &- \beta_{Qloss} \left(\frac{\partial Qloss}{\partial P_i} \right) \end{aligned} \tag{16}$$

A new objective function as well as equality and inequality conditions that take EDRP into consideration can be represented by:

$$Min \sum_{i\in n_g}(C_i(P_{gi})) + \sum_{i\in N_{EDRPi}}(C_i(P_{EDRPi})) \tag{17}$$

Subject to:

$$P_i = P_{gi} - P_{di} + P_{EDRPi} = \sum_{j=1}^{N_b} V_iV_j[G_{ij}\cos(\delta_i-\delta_j) + B_{ij}\sin(\delta_i-\delta_j)]$$
$$\forall i = 1,\ldots,N_b$$
$$Q_i = Q_{gi} - Q_{di} + Q_{EDRPi} = \sum_{j=1}^{N_b} V_iV_j[G_{ij}\sin(\delta_i-\delta_j) - B_{ij}\cos(\delta_i-\delta_j)]$$
$$\forall i = 1,\ldots,N_b \tag{18}$$

$$\begin{aligned} Ploss &= \sum_{i\in N_b}P_{gi} - \sum_{i\in N_b}P_{di} + \sum_{i\in N_{EDRPi}}P_{EDRPi} \\ &= \sum_{i=1}^{N_b}\sum_{j=1}^{N_b}\left\{\begin{array}{l}\frac{R_{ij}}{V_iV_j}[P_iP_j\cos(\delta_i-\delta_j)+Q_iQ_j\cos(\delta_i-\delta_j)- \\ P_iQ_j\sin(\delta_i-\delta_j)+P_jQ_i\sin(\delta_i-\delta_j)]\end{array}\right\} \end{aligned} \tag{19}$$

$$\begin{aligned} Qloss &= \sum_{i\in N_b}Q_{gi} - \sum_{i\in N_b}Q_{di} + \sum_{i\in N_{EDRPi}}Q_{EDRPi} \\ &= \sum_{i=1}^{N_b}\sum_{j=1}^{N_b}\left\{\begin{array}{l}\frac{R_{ij}}{V_iV_j}[P_jQ_i\cos(\delta_i-\delta_j)-P_iP_j\sin(\delta_i-\delta_j)- \\ Q_iQ_j\sin(\delta_i-\delta_j)-P_iQ_j\cos(\delta_i-\delta_j)]\end{array}\right\} \end{aligned} \tag{20}$$

$$P_{gi}^{\min} \leqslant P_{gi} \leqslant P_{gi}^{\max} \tag{21}$$
$$Q_{gi}^{\min} \leqslant Q_{gi} \leqslant Q_{gi}^{\max} \tag{22}$$
$$V_i^{\min} \leqslant V_i \leqslant V_i^{\max} \tag{23}$$
$$\delta_i^{\min} \leqslant \delta_i \leqslant \delta_i^{\max} \tag{24}$$
$$S_{ij} \leqslant S_{ij}^{\max} \tag{25}$$
$$P_{EDRPi}^{\min} \leqslant P_{EDRPi} \leqslant P_{di} \tag{26}$$
$$Q_{EDRPi}^{\min} \leqslant Q_{EDRPi} \leqslant Q_{di} \tag{27}$$

The Lagrangian function incorporating with EDRP for the local marginal price determination can be written as a function of P_i and Q_i as:

$$\begin{aligned} L(P_i,Q_i)^{EDRP} = {} & \sum_{i\in n_g}(C_i(P_{gi})) + \sum_{i\in N_{EDRPi}}(C_i(P_{EDRPi})) + \sum_{i\in N_b}\left(LMP_{pi}^{EDRP}\right) \\ & \times\left[P_i - \sum_{j=1}^{N_b}V_iV_j[G_{ij}\cos(\delta_i-\delta_j)+B_{ij}\sin(\delta_i-\delta_j)]\right] \\ & + \sum_{i\in N_b}(LMP_{qi}^{EDRP}) \times \left[Q_i - \sum_{j=1}^{N_b}V_iV_j[G_{ij}\sin(\delta_i-\delta_j)-B_{ij}\cos(\delta_i-\delta_j)]\right] \\ & + \beta_{Ploss}^{EDRP}\left(\sum_{i\in N_b}P_{gi} + \sum_{i\in N_{EDRPi}}P_{EDRPi} - \sum_{i\in N_b}P_{di}\right. \\ & - \sum_{i=1}^{N_b}\sum_{j=1}^{N_b}\left\{\frac{R_{ij}}{V_iV_j}[P_iP_j\cos(\delta_i-\delta_j)+Q_iQ_j\cos(\delta_i-\delta_j)\right. \\ & \left.\left.-P_iQ_j\sin(\delta_i-\delta_j)+P_jQ_i\sin(\delta_i-\delta_j)]\right\}\right) \\ & + \beta_{Qloss}^{EDRP}\left\{\sum_{i\in N_b}Q_{gi} + \sum_{i\in N_{EDRPi}}Q_{EDRPi} - \sum_{i\in N_b}Q_{di}\right. \\ & - \sum_{i=1}^{N_b}\sum_{j=1}^{N_b}\left\{\frac{R_{ij}}{V_iV_j}[P_jQ_i\cos(\delta_i-\delta_j)-P_iP_j\sin(\delta_i-\delta_j)\right. \\ & \left.\left.-Q_iQ_j\sin(\delta_i-\delta_j)-P_iQ_j\cos(\delta_i-\delta_j)]\right\}\right\} \\ & + \sum_{i=1}^{N_g}\omega_i^{\max EDRP}(P_i^{\max}-P_i) + \sum_{i=1}^{N_g}\omega_i^{\min EDRP}\left(P_i-P_i^{\min}\right) \\ & + \sum_{i=1}^{N_g}\sigma_i^{\max EDRP}(Q_i^{\max}-Q_i) + \sum_{i=1}^{N_g}\sigma_i^{\min EDRP}\left(Q_i-Q_i^{\min}\right) \\ & + \sum_{i=1}^{N_{EDRP}}\psi_i^{\max EDRP}(P_i^{\max}-P_i) + \sum_{i=1}^{N_{EDRP}}\psi_i^{\min EDRP}\left(P_i-P_i^{\min}\right) \\ & + \sum_{i=1}^{N_{EDRP}}\varphi_i^{\max EDRP}(Q_i^{\max}-Q_i) + \sum_{i=1}^{N_{EDRP}}\varphi_i^{\min EDRP}\left(Q_i-Q_i^{\min}\right) \\ & + \sum_{i=1}^{N_b}v_i^{\max EDRP}(V_i^{\max}-V_i) + \sum_{i=1}^{N_b}v_i^{\min EDRP}\left(V_i-V_i^{\min}\right) \\ & + \sum_{i=1}^{N_b}\gamma_i^{\max EDRP}(\delta_i^{\max}-\delta_i) + \sum_{i=1}^{N_b}\gamma_i^{\min EDRP}\left(\delta_i-\delta_i^{\min}\right) \\ & + \sum_{ij=1}^{N_l}\alpha_{ij}^{\max EDRP}\left(S_{ij}^{\max}-S_{ij}\right) \end{aligned} \tag{28}$$

Accordingly, the LMPs at each node considering EDRP cost are given as follows:

$$\begin{aligned} LMP_i^{EDRP} &= \frac{\partial L(P_i,Q_i)}{\partial P_i} = 0 \Rightarrow LMP_i \\ &= \frac{\partial\left(\sum_{i\in n_g}(C_i(P_{gi})) + \sum_{i\in N_{EDRPi}}(C_i(P_{EDRPi}))\right)}{\partial P_i} + \omega_i^{\max EDRP} \\ &\quad - \omega_i^{\min EDRP} + \psi_i^{\max EDRP} - \psi_i^{\min EDRP} \\ &\quad + \beta_{Ploss}^{EDRP}\left(1-\frac{\partial Ploss}{\partial P_i}\right) - \beta_{Qloss}^{EDRP}\left(\frac{\partial Qloss}{\partial P_i}\right) \end{aligned} \tag{29}$$

Dispatch problem with a cost minimization considering lines and generators outages be written as:

$$Min \sum_{i\in N_g - N_{generatorsoutages}}(C_i(P_{gi})) + \sum_{i\in N_{EDRPi}}(C_i(P_{EDRPi})) \tag{30}$$

With before inequality and equality constraint except lines which was outage. The Lagrangian function incorporating with EDRP in emergency state for the local marginal price determination can be written as:

$$\begin{aligned} L(P_i,Q_i)_{EmergencyState}^{EDRP} = {} & \sum_{i\in N_g-N_{generatorsoutages}}(C_i(P_{gi})) + \sum_{i\in N_{EDRPi}}(C_i(P_{EDRPi})) \\ & + \sum_{i\in N_b-N_{generatorsoutages}}\left(LMP_{pi}^{EmegState}\right) \\ & \times\left[P_i - \sum_{j=1}^{N_b-N_{generatorsoutages}}V_iV_j[G_{ij}\cos(\delta_i-\delta_j)\right. \\ & \left.+B_{ij}\sin(\delta_i-\delta_j)]\right] + \sum_{i\in N_b-N_{generatorsoutages}}\left(LMP_{qi}^{EmegState}\right) \\ & \times\left[Q_i - \sum_{j=1}^{N_b-N_{generatorsoutages}}V_iV_j[G_{ij}\sin(\delta_i-\delta_j)\right. \\ & \left.-B_{ij}\cos(\delta_i-\delta_j)]\right] \\ & + \beta_{Ploss}^{EmegState}\left(\sum_{i\in N_b-N_{generatorsoutages}}P_{gi} + \sum_{i\in N_{EDRPi}}P_{EDRPi}\right. \\ & - \sum_{i\in N_b}P_{di} - \sum_{i=1}^{N_b}\sum_{j=1}^{N_b}\left\{\frac{R_{ij}}{V_iV_j}[P_iP_j\cos(\delta_i-\delta_j)\right. \\ & + Q_iQ_j\cos(\delta_i-\delta_j) - P_iQ_j\sin(\delta_i-\delta_j) \\ & \left.\left.+P_jQ_i\sin(\delta_i-\delta_j)]\right\}\right) \\ & + \beta_{Qloss}^{EmegState}\left\{\sum_{i\in N_b-N_{generatorsoutages}}Q_{gi} + \sum_{i\in N_{EDRPi}}Q_{EDRPi}\right. \\ & - \sum_{i\in N_b}Q_{di} - \sum_{i=1}^{N_b}\sum_{j=1}^{N_b}\left\{\frac{R_{ij}}{V_iV_j}[P_jQ_i\cos(\delta_i-\delta_j)\right. \\ & - P_iP_j\sin(\delta_i-\delta_j) - Q_iQ_j\sin(\delta_i-\delta_j) \\ & \left.\left.-P_iQ_j\cos(\delta_i-\delta_j)]\right\}\right\} + \sum_{i=1}^{N_g-N_{generatorsoutages}}\omega_i^{\max EmegState}(P_i^{\max}-P_i) \\ & + \sum_{i=1}^{N_g-N_{generatorsoutages}}\omega_i^{\min EmegState}\left(P_i-P_i^{\min}\right) \\ & + \sum_{i=1}^{N_g-N_{generatorsoutages}}\sigma_i^{\max EmegState}(Q_i^{\max}-Q_i) \\ & + \sum_{i=1}^{N_g-N_{generatorsoutages}}\sigma_i^{\min EmegState}\left(Q_i-Q_i^{\min}\right) \end{aligned}$$

$$
\begin{aligned}
&+\sum_{i=1}^{N_{EDRP}} \psi_i^{\max EmegState}\left(P_i^{\max}-P_i\right)\\
&+\sum_{i=1}^{N_{EDRP}} \psi_i^{\min EmegState}\left(P_i-P_i^{\min}\right)\\
&+\sum_{i=1}^{N_{EDRP}} \varphi_i^{\max EmegState}\left(Q_i^{\max}-Q_i\right)\\
&+\sum_{i=1}^{N_{EDRP}} \varphi_i^{\min EmegState}\left(Q_i-Q_i^{\min}\right)\\
&+\sum_{i=1}^{N_b-N_{generatorsoutages}} \nu_i^{\max EmegState}\left(V_i^{\max}-V_i\right)\\
&+\sum_{i=1}^{N_b-N_{generatorsoutages}} \nu_i^{\min EmegState}\left(V_i-V_i^{\min}\right)\\
&+\sum_{i=1}^{N_b-N_{generatorsoutages}} \gamma_i^{\max EmegState}\left(\delta_i^{\max}-\delta_i\right)\\
&+\sum_{i=1}^{N_b-N_{generatorsoutages}} \gamma_i^{\min EmegState}\left(\delta_i-\delta_i^{\min}\right)\\
&+\sum_{ij=1}^{N_l-N_{lineoutage}} \alpha_{ij}^{\max EmegState}\left(S_{ij}^{\max}-S_{ij}\right)
\end{aligned}
\tag{31}
$$

The LMPs at each node in emergency state are given as follows:

$$
\begin{aligned}
LMP_i^{EmegState} = &\frac{\partial\left(\sum_{i\in N_g-N_{generatorsoutages}}\left(C_i(P_{gi})\right)+\sum_{i\in N_{EDRPi}}\left(C_i(P_{EDRPi})\right)\right)}{\partial P_i}\\
&+\omega_i^{\max EmegState}-\omega_i^{\min EmegState}+\psi_i^{\max EmegState}\\
&-\psi_i^{\min EmegState}+\beta_{Ploss}^{EmegState}\left(1-\frac{\partial Ploss}{\partial P_i}\right)\\
&-\beta_{Qloss}^{EmegState}\left(\frac{\partial Qloss}{\partial P_i}\right)
\end{aligned}
\tag{32}
$$

4. Case study

4.1. Test case results of DRP

The IEEE 9-bus system as depicted in Fig. 2 is used here to show the effect of EDRP program on LMPs and operation cost.

The elasticity coefficients of the loads are shown in Table 1 similar to [14]. The load curve of Mid-Atlantic region of New York network as shown in Fig. 3 was selected for testing and analyzing the effect of EDRP program look like [6].

The load curve is divided into three intervals. Low load period (12:00 am to 9:00 am), off-peak period (10:00 am to 1:00 pm and 7:00 pm to 12:00 am) and the peak period (2:00 pm to 6:00 pm). Fig. 4 shows the load curves before and after implementation of demand response program.

As it shown in Fig. 4, by implementation of DRP based on the difference between elasticities in different periods, loads are shifted from peak periods to valley periods. Without DRP, the system peak load is 315 MW. However, as a result of DRP it is reduced to 303.64 MW.

Figs. 5 and 6 show how implementing DRP helps reduce LMP spikes and operation cost. Note that the highest and lowest LMP without DRP are 24.998 \$/MWh and 16.233 \$/MWh, respectively. With the introduction of DRP, they are changed to 24.099 \$/MWh and 16.889 \$/MWh. Also, the total operation cost of the system for the 24-h period with DRP was 98510.32 \$/MW, however, without DRP is 99427.18 \$/MWh.

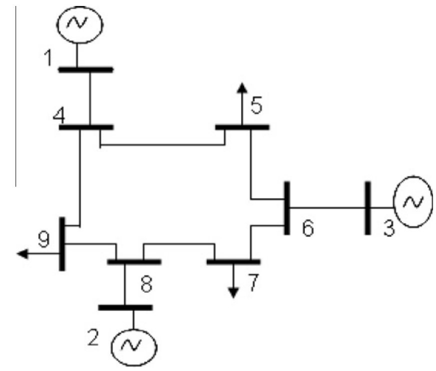

Fig. 2. IEEE 9-bus test system.

Table 1
Self and cross elasticies.

Type	Peak	Off-peak	Low
Peak	−0.02	0.0032	0.0024
Off-peak	0.0032	−0.02	0.002
Low	0.0024	0.002	−0.02

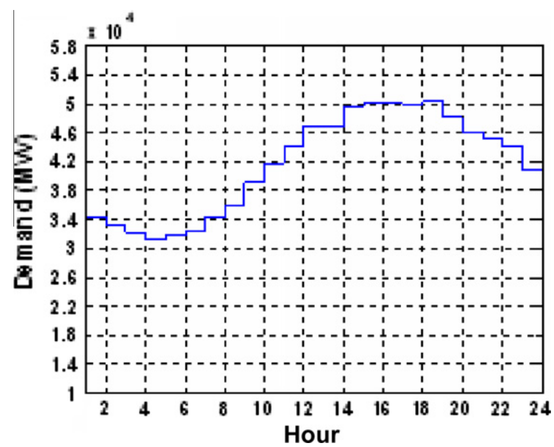

Fig. 3. Load curve of Mid-Atlantic region of New York.

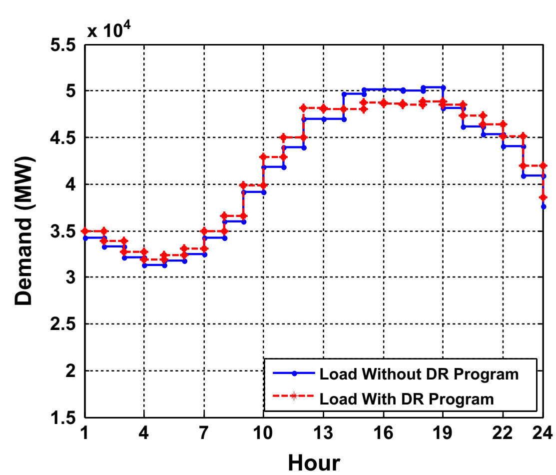

Fig. 4. Load curve without and with DR program.

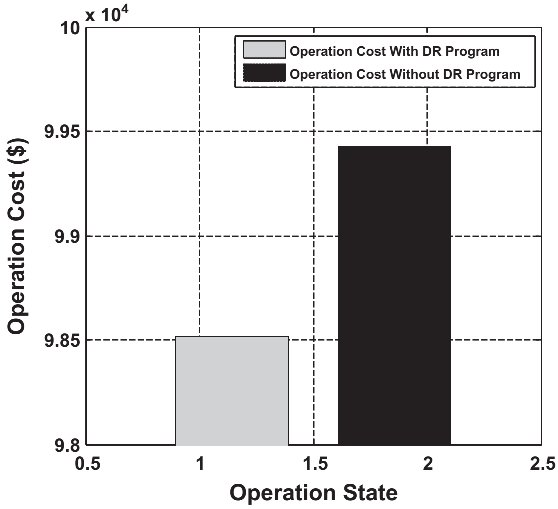

Fig. 5. Load curve without and with DR program.

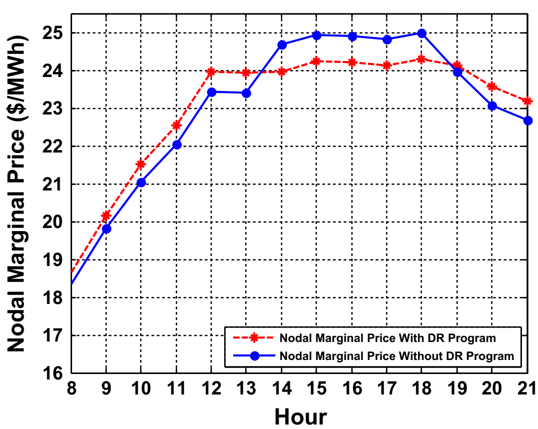

Fig. 6. Load curve without and with DR program.

Table 2
Line number.

Line from bus to bus	1–4	4–5	5–6	3–6	6–7	7–8	8–2	8–9	9–4
Line number	1	2	3	4	5	6	7	8	9

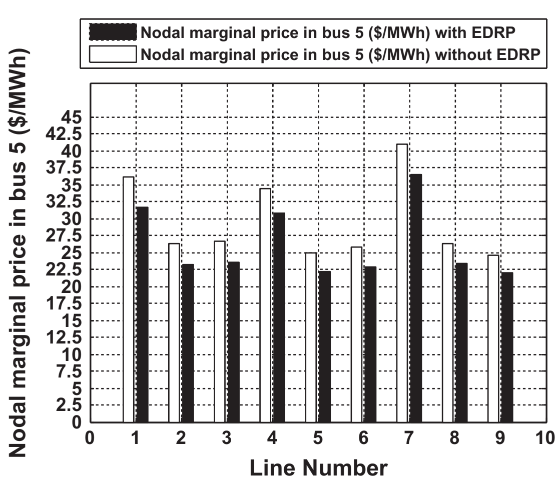

Fig. 7. LMP in bus 5 for first-order line outage.

4.2. Test case results of EDRP

Independent System Operators (ISOs) are particularly interested in EDRP during emerging events as a tool to reduce price spikes. During the system peak hours, in which emergency events such as branches and generators outages occur, the ISO uses EDRP resources in order to prevent system instability and sudden increase of market prices. In this section, the effect of the EDRP

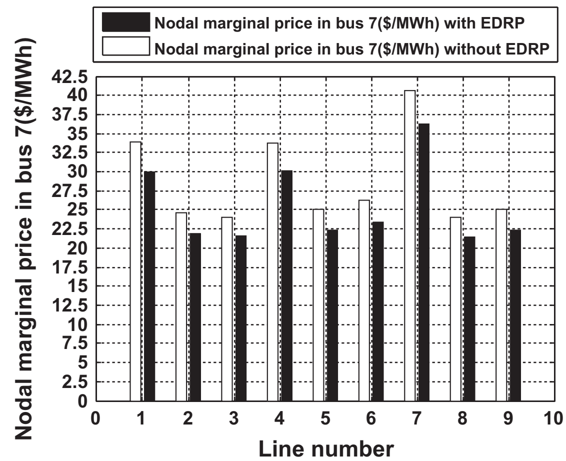

Fig. 8. LMP in bus 7 for first-order line outage.

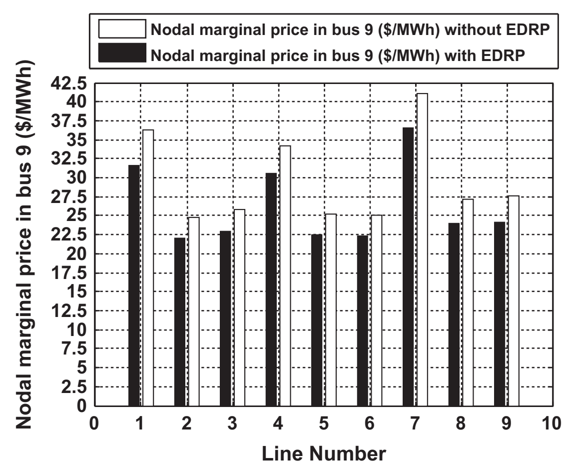

Fig. 9. LMP in bus 9 for first-order line outage.

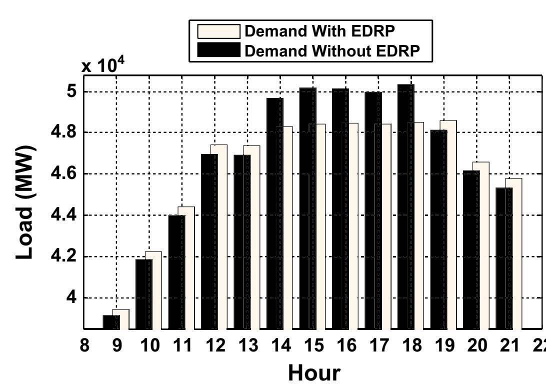

Fig. 10. LMP in bus 9 for first-order line outage.

during emergency events when market prices go high is studied and simulated. The amount of incentive in EDRP program formulation is assumed to be 500 $/MWh used incentive in this study. Several emergency states were created by means of line outage and the corresponding scenarios were simulated with and without EDRP leading to LMPs as shown in Table 2 and Figs. 7–9.

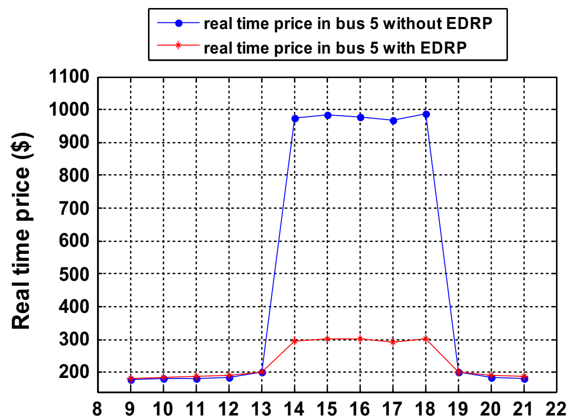

Fig. 11. Real time price in bus 5.

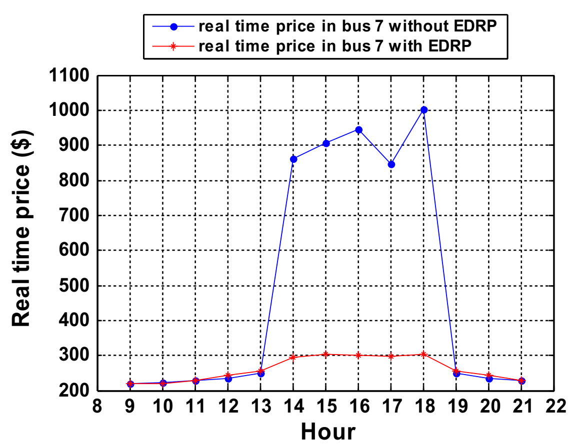

Fig. 12. Real time price in bus 7.

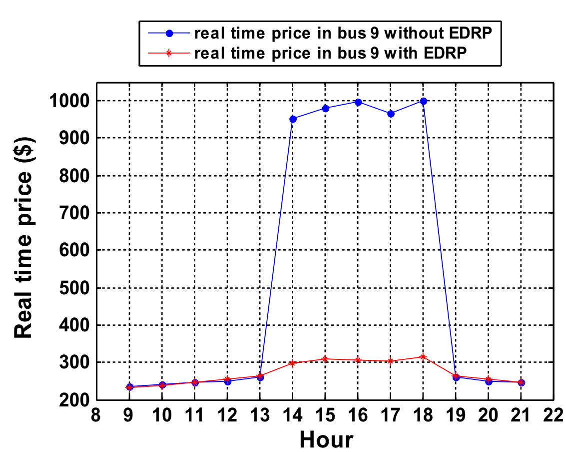

Fig. 13. Real time price in bus 9.

Note that in case of line 2–8 outage, the EDRP has reduced the price spikes by 10.8%. In order to create high price scenarios, the cost characteristics of generation units have been modified. At the end, previous created emergency cases were simulated leasing to LMPs as depicted in Figs. 10–13. In this case, the EDRP has resulted in a significant reduction in price spikes (on average 30% reduction).

5. Conclusion

As a conclusion, in this article the demand respond programs effects with considering an economic model for this program in restructured systems reviewed. At first the effects of this model on spike prices at peak hours in power system with contingency has simulated and analyzed. Actually a new framework using demand response program was presented for price spikes reduction. The results show that by using the effects of consumer's participation, price spikes can be reduced and electric prices increase will be avoided.

Moreover, this paper discussed the effects of demand response program on local marginal price (LMP) spikes and operation cost reduction are evaluated by using emergency demand response program (EDRP) and economic load model, AC-OPF formulation, and local marginal price evaluation techniques. The study results demonstrate the effectiveness of these programs in an electricity market and showing them as appropriate tools in managing the LMPs of the power market more efficiently. Consequently, we can say that solving the problems of electric prices volatility and power supply reduction at system peak hours without interfering of the customers in market is not possible. Consumer participation makes power markets more competitive and enhances market performance.

References

[1] Aflaki K, Jadid S, Shahidehpour M. Electricity restructuring in Iran: achievements and challenges. Electricity J 2009;22(2):74–83.
[2] Shahidehpour M, Yamin H, Li Z. Market operations in electric power systems. New York, NY: Wiley; 2002.
[3] River C. Primer on demand side management. Report for the World Bank; February 2005.
[4] US Department of Energy. Energy policy Act of 2005, section 1252; February 2006.
[5] FERC report. Regulatory commission survey on demand response and time based rate programs/tariffs; August 2006. <www.ferc.gov>.
[6] New York ISO. <www.nyiso.com>.
[7] Hirst E. Reliability benefits of price-responsive demand. IEEE Power Eng Rev 2003;22(11):16–21.
[8] Azami Rahmat, Fard Amir Faraji. Impact of demand response programs on system and nodal reliability of a deregulated power system. In: ICSET-IEEE, 2008, Singapore; 2008.
[9] Wellinghoff J. Collaborative dialog on demand response. FERC report; 12 November 2006. <www.ferc.gov>.
[10] Fahliglu M, Alvarado FL. Designing incentive compatible contracts for effective demand management. IEEE Trans Power Syst 2000;15(4):1255–60.
[11] Affonso CM, Da Silva LCP. Potential benefits of implementing load management to improve power system security. Int J Electr Power Energy Syst 2010;32(6):704–10.
[12] Kirschen DS, Strbac G, Cumperayot P, Mendes D. Factoring the elasticity of demand in electricity prices. IEEE Trans Power Syst 2000;15(2):612–7.
[13] Kirschen DS, Strbac G. Fundamentals of power system economics. John Wiley & Sons; 2004.
[14] Kirschen DS. Demand-side view of electricity markets. IEEE Trans Power Syst 2003;18(2):520–7.
[15] Aalami H, Yousefi GR, Parsa Moghadam M. Demand response model considering EDRP and TOU programs. In: IEEE/PES transmission and distribution conference & exhibition, 2008, Chicago, USA; 2008.
[16] Jokic A, Lazar M, van den Bosch PPJ. Real-time control of power systems using nodal prices. Int J Electr Power Energy Syst 2009;31(9):522–30.
[17] Singh RK, Goswami SK. Optimum allocation of distributed generations based on nodal pricing for profit, loss reduction, and voltage improvement including voltage rise issue. Int J Electr Power Energy Syst 2010;32(6):637–44.

Rahmat Aazami received the B.Sc. and M.Sc. degree in electrical engineering from Shahid Chamran University of Ahvaz, Ahvaz, Iran, in 2007 and University of Tehran, Tehran, Iran in 2009, respectively. Now he is pursuing the Ph.D. degree in electrical engineering in the Tarbiat Modares University (TMU), Tehran, Iran. His areas of interest include power system operation and economics, electricity market analysis and reliability enhancement using load management in restructured power systems.

Kaveh Aflaki (S'08) received his B.S. degree in Electronic Engineering in 2005 and his M.S. degree in Electrical Engineering from Iran university of Science and Technology, Tehran, Iran, in 2008. He is currently pursuing the Ph.D. degree in the Electrical and Computer Engineering Department at the Illinois Institute of Technology (IIT), Chicago. His research interests include power system restructuring and planning, power system management, electricity market, and system optimization. He is graduate student member of IEEE and HKN.

Mahmoud Reza Haghifam (IEEE M'95–SM'06) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering in 1989, 1992, and 1995, respectively. He is a Professor in Power Systems at the Department of Electrical Engineering, Tarbiat Modares University, Tehran, Iran. Also he is a Research Fellow of Alexander Von Humboldt in Germany. He was as Visiting Professor in the University of Calgary, Calgary, AB, Canada in 2003. His main research interests are power system restructuring, power system reliability, and electric distribution system. He has published more than 300 technical papers in these areas. Dr. Haghifam is a senior member IEEE and an IEEE Iran Section Industrial relationship officer. He has been awarded by DAAD and AvH in 2001, 2006, and 2009 for research stays in German universities.