Electric Power Systems Research 132 (2016) 115–124

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Modeling nonlinear incentive-based and price-based demand response programs and implementing on real power markets

Mehdi Rahmani-andebili *

The Holcombe Department of Electrical and Computer Engineering, Clemson University, Clemson, SC 29634, USA

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form 3 November 2015
Accepted 12 November 2015
Available online 17 December 2015

Keywords:
Incentive-based demand response programs
Nonlinear modeling
Price-based demand response programs
Real power markets
Responsive load behavioral models

ABSTRACT

The most important factor in the demand side management (DSM) is realistically modeling reaction of the responsive load respect to the different plans of the demand response (DR) programs introduced by the DR provider. Due to the economic and social aspects, the responsive load behavioural models (RLBMs) might be different in every power market. In this study, linear and nonlinear modellings for the incentive-based DR (IBDR) programs and the price-based DR (PBDR) programs are presented and implemented on several real power markets. Herein, results of the implementation of DR programs on the power markets for different participation levels of the responsive load in the DR programs are studied. In addition, value of the possible errors in the defined indices due to unpractical modeling of the responsive load behaviour are probed, and also optimal schemes of the IBDR and PBDR programs are investigated in every power market from different viewpoints.

1. Introduction

ModelingSmart Grid is the future development of power system worldwide [1]. One of the main aims for implementation of smart grid is facilitating demand side management (DSM), since it helps customers to consume electricity in a more clean and efficient way through interoperability between them and power utilities [2]. DSM is normally considered as the first precedence in energy policy decisions due to its benefits from economic and environmental viewpoints [3]. DSM provides short-term responses to electricity market conditions to reduce overall costs of energy supply, increase reserve margin, mitigate price volatility, and achieves environmental goals by deferring commitment of polluted units leading to increased energy efficiency and reduced greenhouse gas emissions [4]. According to the Federal Energy Regulatory Commission, demand response (DR) is defined as: “Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” [5].

Smart grid vision is to enable more active end-user participation rather than just considering them passive consumption points [6,7]. Based on two-way communications, smart metering can collect detailed information of end-users’ electricity consumption patterns and provide automatic control to the household appliances [8]. On the other hand, it has been proved that industrial and commercial buildings have large potential in DR [9].

A comprehensive survey on demand response has been done in [10] that includes different tariffs taken by the power utilities to incentivize consumers to reschedule their energy usage patterns, mathematical models and problems in the literatures, the potential challenges, and the future research directions in the context of DR. Several studies have investigated implementation potential of DR programs on some case studies [11–14]. The U.S. federal energy regulatory commission estimates that the contribution from existing demand-side resources (DSRs) in the U.S. is around 41000 MW equal to 5.8% of the 2008 summer peak demand [11]. A study presented in [12] shows that incentive-based demand response (IBDR) programs are responsible for 93% of peak load reduction in the U.S. The presented study in [13], utilizes information and communication technologies (ICT) to facilitate participation of customers in DR program. In [14], potential of proposed smart metering communication system in the U.K. for reporting available DR from domestic appliances has been investigated. In [15], potential of DR programs for addressing the variability issue of the renewables has been reviewed.

* Tel.: +1 864 643 7803.
E-mail address: mehdir@g.clemson.edu

http://dx.doi.org/10.1016/j.epsr.2015.11.006

Nomenclature

$D^{\text{Initial}}_{\text{RLBM}}(.)$ Initial demand level.
$D^{\text{DR}}_{\text{RLBM}}(.)$ Demand level after implementation of the DR programs considering RLBM.
$D^{\text{Contract}}(.)$ Value of the demand assigned in the contract to be curtailed in the mandatory IBDR program.
DR Demand response program.
$E(.,.)$ Price elasticity of demand of the responsive load.
ES Value of saved energy.
Exp Exponential behavioral model.
GSF(.) Gross surplus function of the responsive load.
IBDR Incentive-based demand response.
LF Value of load factor.
Lin Linear behavioral model.
Log Logarithmic behavioral model.
NSF(.) Net surplus function of the responsive load.
$\text{NSF}_1(.)$ First term of the net surplus function related to selling the produced commodities and participating in the PBDR program.
$\text{NSF}_2(.)$ Second term of the net surplus function related to participation of the responsive load in the voluntary IBDR program.
$\text{NSF}_3(.)$ Third term of the net surplus function related to participation of the responsive load in the mandatory IBDR program.
NT Number of hours of a day.
Pow Power behavioral model.
PBDR Price-based demand response.
RLBM Responsive load behavioral model.
ST Set of hours of a day.
$u(t)$ Binary value used to indicate if the responsive load meets its obligation for demand reduction or not.
$z^{\text{V-IBDR}}$ Value of incentive at peak period related to the voluntary incentive-based demand response.
z^{PBDR} Variable used to modify electricity price in the price-based demand response program.
π^{Initial} Initial price of the electricity.
$\pi^{\text{PBDR}}(.)$ Electricity price in the price-based demand response program.
$\xi^{\text{M-IBDR}}(.)$ Value of incentive in the mandatory incentive-based demand response program.
$\xi^{\text{V-IBDR}}(.)$ Value of incentive in the voluntary incentive-based demand response program.
$\varphi^{\text{M-IBDR}}(.)$ Value of penalty in the mandatory incentive-based demand response program.
Ω Sum of the absolute value of the errors in the expected demand level.
δ_1 Minimum value of the load demand.
δ_2 Maximum value of the load demand.

Some papers have investigated DR programs in market environment [16–21]. In [16], home appliances are scheduled to minimize electricity cost and earn the incentive of DR program. In [17], price-responsive demand has been incorporated in a real-time balancing market with a pay-as-bid pricing scheme. In [18], a model of DR with price-responsive demand bids in energy and spinning reserve markets has been presented to minimize total cost of the system. In [19], DR has been treated as a public good to be exchanged between DR buyers and sellers in a pool-based market. In [20], a strategic bidding model for the load serving entities has been proposed to maximize their profit by providing coupon-based DR programs in presence of the wind power. Also, in [21], the advantages and disadvantages of the coupon-based DR programs have been discussed in comparison with the existing DR programs.

In [22–26], DR programs have been investigated in the unit commitment (UC) problem to decrease operation cost of the system. In [22,23], DR program has been modeled based on biding strategy and price elasticity of demand, and also in [24–26], linear behavioral model of the responsive load has been investigated in the DR program. Nonetheless, in all the above mentioned studies, nonlinear DR programs and nonlinear responsive load behavior have not been modeled and investigated.

In this study, the comprehensive modelings of voluntary and mandatory DR programs including IBDR programs and price-based demand response (PBDR) programs proportional to linear and nonlinear behavioral models of the responsive load respect to the introduced schemes of DR programs are presented. The introduced models for the IBDR and PBDR programs are implemented on several real power markets including Electric Reliability Council of Texas (ERCOT), New York Independent System Operator (NYISO), Pennsylvania, Jersey, Maryland (PJM), and Independent System Operator New England (ISO-NE) markets, and then the consequences are analyzed. Moreover, different participation levels of the responsive load in DR programs are investigated. In addition, the possible error in value of the defined indices such as load factor, energy saving, and demand level due to considering unrealistic behavioral models are calculated. Furthermore, optimal schemes of the IBDR and PBDR programs from maximum load factor and maximum energy saving viewpoints are investigated. It is noteworthy to mention that, in this study, values of all the variables and parameters are presented in per unit, and also all the calculations are done in per unit system to keep the comprehensiveness of the modelings and studies.

The rest of the paper is outlined as follows. In Section 2, the linear and nonlinear IBDR and PBDR programs are modeled. Determination of the different periods, the electricity pricing in the PBDR programs, the reward scheme in the IBDR programs, and the evaluation indices are presented in Section 3. The simulation results are given in Section 4, and finally the study is concluded in Section 5.

2. Modeling linear and nonlinear IBDR and PBDR programs

Price elasticity of demand is defined as the demand sensitivity respect to the price [27].

$$E = \frac{\partial D/D^{\text{Initial}}}{\partial \pi/\pi^{\text{Initial}}} = \frac{\partial D}{\partial \pi} \times \frac{\pi^{\text{Initial}}}{D^{\text{Initial}}} \quad (1)$$

where, D^{Initial} is the initial demand level, D is the demand level after introducing the new price, π^{Initial} is the initial price, and π is value of the new price.

If the electricity price varies at different periods or there is an incentive for demand reduction at special period of time (peak period), the responsive load reactions are as follow [28]:

- One part of demand of the responsive load (such as lighting demand) has single period sensitivity, since it cannot be transferred to other periods and it can be only "on" or "off" in the same period. This part of demand is called single period elastic load. Elasticity of such demand that does not has any sensitivity to the electricity prices at other periods is called "self-elasticity". Value of self-elasticity is negative.
- Another part of demand of the responsive load has multi-period sensitivity, since it can be transferred from one period to other periods. This part of demand is called multi-period elastic load. Elasticity of this part of demand, which has sensitivity to the electricity prices at different periods, is called "cross elasticity". Value of cross elasticity is positive.