Applied Energy 96 (2012) 161–170

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

# Optimal combined scheduling of generation and demand response with demand resource constraints

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ARTICLE INFO

*Article history:*
Received 13 June 2011
Received in revised form 29 November 2011
Accepted 25 December 2011
Available online 23 January 2012

*Keywords:*
Demand response
Demand resources
Demand response scheduling
Optimal scheduling
Demand response constraints

ABSTRACT

Demand response (DR) extends customer participation to power systems and results in a paradigm shift from simplex to interactive operation in power systems due to the advancement of smart grid technology. Therefore, it is important to model the customer characteristics in DR. This paper proposes customer information as the registration and participation information of DR, thus providing indices for evaluating customer response, such as DR magnitude, duration, frequency and marginal cost. The customer response characteristics are modeled from this information. This paper also introduces the new concept of virtual generation resources, whose marginal costs are calculated in the same manner as conventional generation marginal costs, according to customer information. Finally, some of the DR constraints are manipulated and expressed using the information modeled in this paper with various status flags. Optimal scheduling, combined with generation and DR, is proposed by minimizing the system operation cost, including generation and DR costs, with the generation and DR constraints developed in this paper.


## 1. Introduction

In current power systems, the efficient use of demand side resources has become important due to the restrictions for utilizing conventional generation resources. In addition, the recent advancements in smart grid technology, including auto-metering and communication, make it feasible to develop demand response (DR) with a program format that uses demand side resources practically. DR can be defined as the changes in electric usage by end-use customers compared to their normal consumption patterns [1]. According to the definition, the primary agents of DR are not the operators but the customers, who have the ability to exert favorable influences, such as improving system reliability and lowering the electric price, by participating in a Demand Response Program (DRP) [1,2]. DR allows the customer participation to extend to the power system operation, and the customers can play a key role in shifting the paradigm in the power systems because they have the ability to voluntarily control the loads as demand resources when the peak load increases, as opposed to the system passively supporting an increasing load with generation resources. In order to efficiently utilize the demand resources, it is important to model the customer characteristics in DR. Recent research [2] shows how customer behaviors can be modeled using an elasticity matrix composed of the price-elasticity of the demand. Refs. [3–9] show that customer responses have a positive influence on the power market performance, nodal price and reliability indices, available transfer capability and spinning reserve, based on the reference method [2]. Refs. [2–9] are seen as merely modeling customer response according to the changes in electricity price during a specific period of the day based on the constant elasticity matrix. In practical terms, however, the assumption of a constant elasticity matrix within a certain specific period is unreasonable, and moreover, the frequency of DR has yet to be modeled and restrictive results may be incurred by a method using an elasticity matrix. In addition, a lack of available information on response characteristics has the effect of incredibility of those methods because the price-elasticity of demand requires high credibility. For this reason, DRP operators request customer information necessary to operate the DRP. As an example, NYISO (New York Independent System Operator) is required to provide interruptible load rating, reduction lasting time, and response time [11,12]. In this paper, aggregated information and their relationships are modeled in a closed form expression. This paper also introduces the concept of virtual generation resources converted from demand resources, with their marginal cost calculated according to customer information. Some constraints of DR are manipulated and expressed using the information modeled with various status flags. Optimal scheduling, combined with generation and DR, is proposed by minimizing the system operation cost, including DR cost as well as conventional generation cost, with the generation and DR constraints developed in this paper.

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0306-2619/$ - see front matter 
doi:10.1016/j.apenergy.2011.12.075

## 2. Customer information

Demand resources desiring to participate in a DRP should provide some initial information on the demand resource characteristics prior to a DRP [11,12]. However, when a DR event is issued, the actual DRP response characteristics may not be identical to the initial information due to some of the demand resource constraints such as the capacity for available lasting response, automated or non-automated metering status, and the business schedule of individual customers. Therefore, it is necessary to collect historical DR data which includes the responsive characteristics of the demand resources after a DRP.

Generally, DR customer information can be divided into registration and participation information, used for more efficiently and accurately evaluating demand side resources [11,12]. Registration information is defined as a customer's initial information prior to registration, and participation information is the historical data collected after a DRP event, as shown in Table 1.

In this paper, we attempt to express the informational relationships using closed form equations, which include status flags for commitment state and beginning and ending states.

For the registration information, DR magnitude $M^j$ [MW] is the maximum demand reduction which customer $j$ is able to achieve. Duration ($D^j_{\min}, D^j_{\max}$ [h]) is the period of demand reduction available per a DR event, consisting of minimum and maximum durations. Frequency $Fj$ [freq/yr] is the maximum number of yearly participation events in the DRP for customer $j$.

For the participation information, participation rate (PR) is defined as the ratio of $j$ customer's load reductions to the DR magnitude at time $t$ and can be represented by

$$\mathrm{PR}^j(t) = \frac{\mathrm{DR}^j(t)}{M^j(t)} \cdot s^j(t), \tag{1}$$

where $\mathrm{DR}^j(t)$ is the load reduction of customer $j$ at time $t$ (MW), and $s^j(t)$ is the DR commitment flag, either a 1 or 0 dependent on whether or not customer $j$ reduces their demand at time $t$. Participation rate denotes the actual reduction level compared with the maximum DR magnitude available to be reduced.

Load response rate (LRR) is similarly defined as the ratio of $j$ customer's load reduction to the customer baseline load at time $t$ and can be represented by

$$\mathrm{LRR}^j(t) = \frac{\mathrm{DR}^j(t)}{\mathrm{CBL}^j(t)} s^j(t), \tag{2}$$

where $\mathrm{CBL}^j(t)$ is the customer baseline load (CBL) at time $t$, which is the average hourly energy consumption and is used to determine the level of load curtailment [11,12]. Load reduction is measured as the difference between the customer baseline load and the actual metered usage for a DR event. LRR denotes the ratio of load changes after a DR, to the total load. LRR can be used to calculate the price elasticity.

DR average duration [h/freq] is defined as the lasting time of load reduction per DR customer participation and can be represented as

$$d^j = \frac{\sum_{t\in T} s^j(t)}{\sum_{t\in T} b^j(t)}, \tag{3}$$

where $b^j(t)$ and $e^j(t)$ are the beginning and ending flags of a DR, respectively. The flags are set to 1 when customer $j$ starts and ends reduction.

DR frequency rate [freq/h] is the number of participation events during a given time and can be represented as

$$f^j = \frac{\sum_{t\in T} b^j(t)}{T}, \tag{4}$$

where $T$ is the length of time of the study in hours.

Fig. 1 illustrates situations for which DR events were issued and customer $j$ responded to the corresponding DR events, where the first DR event occurred from hours 11 to 13 and the second event from hours 17 to 19. Customer $j$ reduced his load by as much as $\mathrm{DR}^j(t)$ from $\mathrm{CBL}^j(t)$ during the DR events and did not participate at hour 19. The DR commitment flag for customer $j$ was 1 when he reduced his demand. The DR beginning and ending flags were set to 1 when starting and finishing reduction, respectively. PR and LRR were calculated using the definitions stated above, where DR average duration and DR frequency were 2.5 and 0.0833, respectively.

**Table 1**
Demand response customer information.

| Registration information | Participation information |
|---|---|
| DR magnitude | Participation rate |
| Duration | Load response rate |
| Frequency | DR average duration |
| | DR frequency rate |
| | Marginal cost |

## 3. Marginal cost of demand resources

This paper proposes the transformation of the demand reductions of demand resources into virtual generations of units. Increased demand reduction can be treated as an equivalent generation resource. It is able to replace the generation resource having a higher marginal cost by comparing the marginal cost of demand reduction and generation resource.

Fig. 2 shows supply and demand curves which denote the marginal cost of generation and load, respectively. The vertical line of the demand curve shows that none of the demand resources responded to the electricity price [10]. The variables $\pi^j_l$ and $\pi^j_h$ are the electricity prices when customer $j$ started and finished responding to the DRP event, respectively. When a customer responds to the DRP, the load reduction, as much as $\mathrm{DR}^j(t)$ from $\mathrm{CBL}^j(t)$, creates the negative slope in the demand curve, demonstrating the characteristics of a typical demand curve. The curve shows that price-responsive customers have a finite marginal value of willingness to pay. The new vertical line shifted by an amount equal to DR represents infinite marginal values of price taking customers. Furthermore, the area below the negative slope represents the DR costs of all of the demand resources used in the DRP.

Demand reduction can be treated as virtual generation by calculating the marginal cost of the demand reduction. It can be consider that the marginal value of demand resources increases according to the amount of DR, i.e., demand reduction, and the negative quantity of the demand reduction resulting from the DR can be converted to a positive slope in the DR in order to draw an analogy with the supply curve, as shown in Fig. 3. The marginal cost, $mc^j$, of demand resources is the function of the load reduction of customer $j$, $dr^j$, and can be represented from Fig. 3 as

$$mc^j = \frac{\pi^j_h(t) - \pi^j_l(t)}{\mathrm{DR}^j(t)} s^j(t) dr^j + \pi^j_l(t) s^j(t), \tag{5}$$

where $\pi^j_l$ and $\pi^j_h$ are the electricity prices when customer $j$ starts and finishes responding to the DRP, respectively.

The linear expression of (5) can be rewritten, for simplicity, as

$$mc^j = \alpha^j(t) dr^j + \beta^j(t), \tag{6}$$

where $\alpha^j(t)$ and $\beta^j(t)$ are the first order coefficient and constant, respectively, of the marginal cost function of customer $j$ and can be determined using (9) and (10), respectively.