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Design of capacity incentive and energy compensation for demand response programs

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Abstract. Variability and Uncertainties caused by renewable energy sources have called for large amount of balancing services. Demand side resources (DSRs) can be a good alternative of traditional generating units to provide balancing service. In the areas where the electricity market has not been fully established, e.g., China, DSRs can help balance the power system with incentive-based demand response programs. However, there is a lack of information about the interruption cost of consumers in these areas, making it hard to determine the rational amount of capacity incentive and energy compensation for the participants of demand response programs. This paper proposes an algorithm to calculate the amount of capacity incentive and energy compensation for demand response programs when there lacks the information about interruption cost. Available statistical information of interruption cost in referenced areas is selected as the referenced data. Interruption cost of the targeted area is converted from the referenced area by product per electricity consumption. On this basis, capacity incentive and energy compensation are obtained to minimize the payment to consumers. Moreover, the loss of consumers is guaranteed to be covered by the revenue they earned from load serving entities.

1. Introduction

The increasing penetration of renewable energy resources and the construction of ultra high voltage transmission system have added more random factors into the power system [1]. These random factors can possibly decrease the level of reliability of the whole system, which calls for more balancing resources than usual [2]. The large outages, including the bipolar block of the ultra high voltage direct current transmission system, will lead to a large shortage of electric power generations. However, these outages happen quiet rare that increasing the generation-side resources is uneconomical [1]. The demand side resources (DSRs) is an alternative of traditional generating resources to provide balancing services.

In practice, DSRs provide balancing services through demand response programs, which enable consumers for reducing their electricity usage when requested by the system operator [3]. Many countries and areas have already carried out experimental studies of demand response programs, which can be divided into two types:1) price-based demand response that relies on consumers to change their consumption according to time-varying electricity prices [4]; and 2) incentive-based

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demand response programs that motivate consumers to reduce their electricity usage with incentive paid for the available interruptible capacity and compensation paid for the actual reduced energy consumption after a demand response event [4]. For the countries where the construction of electricity market is still at the preliminary stage, e.g., China, the price based demand response is infeasible because there doesn’t exist a time varying electricity price [5]. Therefore, this paper focus on the incentive-based demand response, which is practical for China to implement demand response programs by setting up rational amount of capacity incentive and energy compensation.

Determining the rational amount of capacity incentive and energy compensation is crucial for arousing the enthusiasm of consumers to join in demand response programs. Reference [6] proposes a benefit sharing incentive scheme at the retail level which involves the use of a publicly broadcast grid state index implemented by the California Independent System Operator. Targeting on issue of the breach of interruptible contract, reference [7] combines punishment rule in compensation price. Reference [8] describes a practical approach to identify nodal price compensation payment for nodal consumers who are willing to reduce their energy consumption. The above approaches calculate the capacity incentive and energy compensation according to the loss of benefit and the revenue that the consumers earned from the demand response programs. However, there lacks the necessary statistical information about the interruption cost of consumers in China, making it hard to calculate the incentive and compensation values. The existing demand response cases in other countries and areas can be the reference for the implementation of demand response program. Due to different levels of economic development, it is impractical and illogical to directly apply the referenced compensation and incentive to the targeted areas.

Because of the uncertainties brought by the ultra high voltage transmission system in China, using demand side resources to provide the balancing services is necessary in case of circumstance. Many provinces have already finished the construction of demand response equipment for many consumers, which can successfully control the load beyond seconds once the outage happens. This paper proposes an algorithm to calculate the amount of capacity incentive and energy compensation for demand response programs when there lacks the information about interruption cost. The statistical information in existing demand response programs is selected as the referenced data. Product per electricity consumption is set as the ratio to converse interruption cost from the referenced areas to the targeted areas. Based on this ratio, the estimated interruption cost corresponding to different interruption duration can be calculated. Further, capacity incentive and energy compensation are obtained to minimize the payment to consumers. Meanwhile, the loss of consumers is guaranteed to be covered by the revenue they earned from load serving entities.

The remainder of this paper is organized as follows. Section 2 presents the method that converses interruption cost from the referenced areas to the targeted areas. Section 3 introduces the model to calculate capacity incentive and energy compensation for the demand response participants. Case studies are carried out in Section 4 to illustrate the proposed technique to calculate capacity incentive and energy compensation for demand response programs in China. Finally, conclusions are drawn in Section 5.

2. Estimation of interruption cost with product per electricity consumption

Demand side resources provide reserve services by interrupting the electricity usage for a certain amount of time. Such interruption will lead to the loss of customers’ benefit, which is represented by the interruption cost. Interruption cost is directly related to the consumers’ production efficiency. The production efficiency differs greatly with different countries and different time periods. Hence, interruption cost of the referenced areas in certain time should be converted before it is used to estimate the interruption cost in the targeted area. The production efficiency can be approximated as the product output corresponding to one kilowatt-hour of electricity consumption, which is named as product per electricity consumption (PEC) and is represented by

$$PEC(\tau) = PDT(\tau)\cdot\left(EC(\tau)\right)^{-1} \tag{1}$$

where τ is the time interval to calculate the product value and electricity consumption. $PDT(\tau)$ denotes the product of consumers during the time interval τ . $EC(\tau)$ denotes the electricity consumption of the consumers during the time interval τ. Interruption cost various with different time when the interruption occurs. In the early stages of the implementation of demand response, τ is selected to be longer so that the compensation policy will not change a lot. In this way, the policy can be accepted by consumers much more easily. After the demand response policy has been accepted by most consumers, smaller τ can be gradually adopted. This enables the incentive and compensation to be set with different seasons and different type of consumers.

Denote PEC^* as the product per electricity consumption in a referenced area. The interruption cost in this area is denoted as C_{loss}^*. The interruption cost of the targeted area is derived from the data of the referenced area as follows:

$$C_{loss}(\tau) = C_{loss}^*(\tau) \cdot PEC(\tau) \cdot \left(PEC^*(\tau)\right)^{-1} \tag{2}$$

3. Capacity incentive and energy compensation for the demand response participants

3.1. Compensation received by the consumers

The consumers' interruption cost is non-linear with the duration of interruption [8]. Therefore, the amount of incentive and compensation should also be determined according to the duration of interruption. Assuming that the total available interruptible capacity of all the consumers is IL_{total}. The incentive for the available interruptible capacity is CP_C (CNY/kW), the compensation for the actual reduced energy consumption is CP_E (CNY/kWh). The number of interruption is N in a year. The interruptible capacity of the ***i-th*** demand response event is IL_i and the corresponding duration of interruption is DT_i. The participants' revenue is the sum of the capacity incentives and energy compensation:

$$\text{Revenue} = CP_C \cdot IL_{total} + \sum_{i=1}^{N} CP_E \cdot IL_i \cdot DT_i \tag{3}$$

3.2. Interruption cost of all the demand response participants

Total interruption cost of all the demand response participants in a year is :

$$\text{Cost} = \sum_{i=1}^{N} C_{loss}(DT_i) \cdot IL_i \tag{4}$$

The revenue consumers earned should cover the interruption cost, that is:

$$CP_C \cdot IL_{total} + \sum_{i=1}^{N} (CP_E \cdot DT_i - C_{loss}(DT_i)) \cdot IL_i \geq 0 \tag{5}$$

In worst cases, all the available interruptible capacity should be deployed. Hence, the sum of actual interruptible capacity is expressed as:

$$\sum_{i=1}^{N} IL_i = N \cdot IL_{total} \tag{6}$$

Normally, the energy compensation is calculated at regular time intervals (e.g., 1hour). In this case, $CP_E \times DT_i - C_{loss}(DT_i)$ is a constant value. Consequently, equation (5) is converted to：

$$CP_C + (CP_E \cdot DT_i - C_{loss}(DT_i)) \cdot N \geq 0 \tag{7}$$

Load serving entities tend to minimize their operation cost, in which the compensation and incentive paid to the consumers are included. Hence, the capacity incentive and energy compensation paid to the consumers is expected to be minimized:

$$\text{Min} \qquad CP_C \cdot IL_{total} + \sum_{i=1}^{N} CP_E \cdot DT_i \cdot IL_i \tag{8}$$

Therefore, according to (5)-(8), the capacity incentive and energy compensation satisfy the following constraint:

$$CP_E = (C_{loss}(DT_i)\cdot N - CP_C)\cdot(N\cdot DT_i)^{-1} \tag{9}$$

4. Case study

Considering that industrial consumers are the main participants of demand response programs in China at present, this paper takes industrial consumers as examples to illustrate the proposed technique. The interruption cost from IEEE-reliability test system (IEEE-RTS), which contains interruption cost of different types of consumers with different interruption duration in Canada, is the most reliable and commonly used data in existing researches [9], [10]. Hence, interruption cost revealed in IEEE-RTS is chosen as the referenced data and is depicted as figure 1 [9]. Two areas from the east of China, i.e., Zhejiang Province and Jiangsu Province, are selected to calculate the capacity incentive and energy compensation. Case1 is the area of high level of industrial production. By contrast, case 2 is the area of lower level of industrial production than that in case 1. The statistical data of industrial production in these two areas over a year is shown in table 1.

Table 1. The statistical data of industrial production in Zhejiang and Jiangsu over a year.

Case No.	Area	*PDT* (billion CNY)	*EC* (TWh)
Case 1	Zhejiang	6722.24 [11]	276.14 [11]
Case 2	Jiangsu	15778.95 [12]	408.14 [12]

4.1. Estimation of interruption cost in the targeted areas

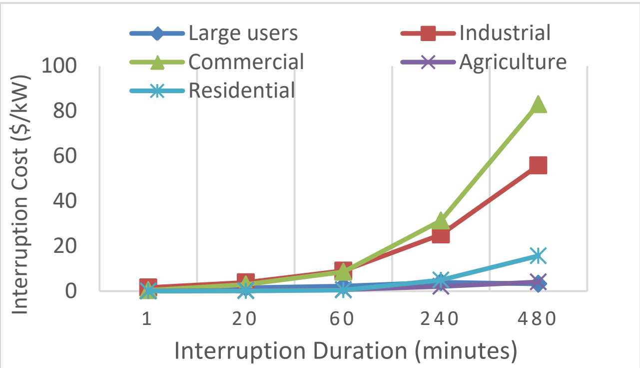

Figure 1. Interruption cost for various types of consumers in Canada [9].

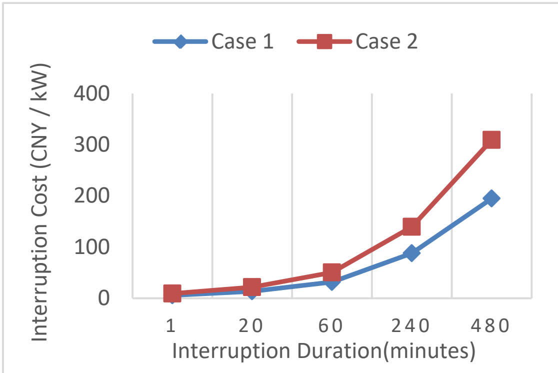

Figure 2. Interruption cost of industrial consumers in two areas.

Table 2. Interruption cost corresponding to different interruption duration in Case1 and Case 2.

Interruption Duration (minutes)	Interruption Cost (CNY / kW)	
	Case 1	Case 2
1	5.67	9.00
20	13.49	21.43
60	31.70	50.34
240	87.81	139.45
480	194.75	309.28

Interruption cost of industrial consumers in two areas, obtained from equation (1)-(2), is depicted in figure 2 and table 2. On the one hand, figure 1 and figure 2 demonstrate that the interruption cost increases with longer interruption duration. On the other hand, table 1 shows that *PDT* in case 1 is lower than that in case 2, correspondingly, figure 2 shows that the interruption cost in case 1 is lower than that in case 2. When the interruption duration reaches 480 minutes, table 2 shows that the interruption cost of case 2 reaches 309.28 (CNY/kW), which is much higher than that in case 1 (194.75 (CNY/kW)). Hence, it is advised that the consumers with lower production efficiency have higher priority to be curtailed, especially when the interruption duration is longer.

4.2. Calculation of capacity incentive and energy compensation in the targeted areas

According to equation (9), we can see that there exists constraints between capacity incentive, energy compensation, number of interruption and duration of interruption. We choose one hour as duration of interruption, the relationship between capacity incentive, energy compensation and number of interruption in case 1 can be seen in figure 3. Figure 3 shows that energy compensation increases with the increase of interruption number and the decrease of capacity incentive. With the increasing of energy compensation, its value approaches 31.74 (CNY/kWh), which is the interruption cost illustrated in table 2.

The capacity incentive for industrial consumers in a pilot study conducted in Jiangsu Province in 2016 is 20 (CNY / kW) [13]. When the capacity incentive is set as 20 (CNY / kW), we can obtain the energy compensation corresponding to different number of interruption in case1 and case 2. The results are illustrated in table 3 and figure 4. It can be seen from figure 4 that the energy compensation increases with the increase of interruption number. The magnitude of such increase becomes smaller with the increase of interruption number. When the interruption number is larger than twice, table 3 shows that the energy compensation in case 1 and case 2 is around 26 (CNY / kWh) and 45 (CNY / kWh), respectively. We can conclude that energy compensation is closely related to the type of consumers and their production level. The number of interruptions and the regional economic development level have to be balanced when determining the proper amount of energy compensation and capacity incentive.

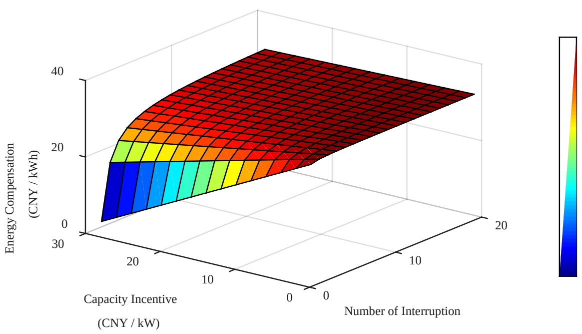

Figure 3. The relationship between capacity incentive, energy compensation and number of interruption in Case 1.

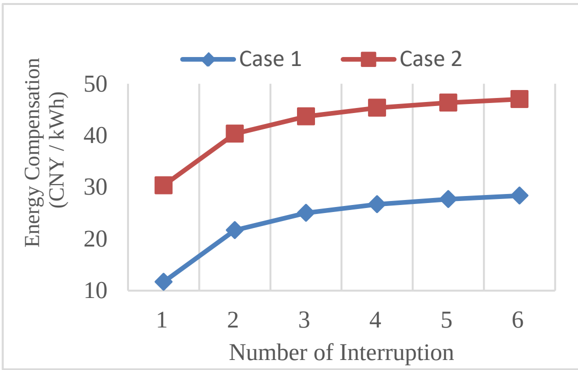

Figure 4. Energy compensation in case 1 and case 2 when capacity incentive is 20 CNY / kW.

Table 3. Energy compensation corresponding to different interruption number in case1 and case 2.

Interruption Number	Energy Compensation (CNY / kWh)	
	Case 1	Case 2
1	11.70	30.34
2	21.70	40.34
3	25.03	43.68
4	26.70	45.34
5	27.70	46.34
6	28.37	47.01

5. Conclusions

Determining a rational amount of capacity incentive and energy compensation is the first step for the implementation of demand response. This paper converses interruption cost from the referenced areas to the targeted areas with product per electricity consumption. On this basis, capacity incentive and energy compensation are calculated to minimize the payment to consumers. The loss of consumers is guaranteed to be covered by the revenue they earned from load serving entities. Case studies are conducted based on the current demand response programs in Jiangsu Province and Zhejiang Province. Simulation results indicate that the proposed algorithm can reflect the influence of different economic development level in different areas. For the areas with lower level of economic development, the energy compensation and capacity incentive are lower, which means the enthusiasm of consumers are more likely to be aroused to join in the demand response programs. Constrains among the number of interruptions, energy compensation and capacity incentive have to be balanced. The proposed method can provide guidance for the implementation of demand response programs in areas where the interruption cost of consumers in not available.

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