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# **A Demand Response Scheme for Wind Integrated Power System Based on Mechanism Design Theory**

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Abstract. The increasing integration of high penetration of wind power into power systems have created great challenges for stable operation of the power system. It is important to design a reasonable demand response scheme (DRS) to make decision the optimal load relief. specially, for the wind power suppliers (WPS) and their customers (WPSC). Therefore, this paper proposes a demand response scheme for wind integrated power system based on mechanism design theory. Firstly, we derive the outage cost function and incentive function modeled by the two variables: the customers' type parameter and the location value. Secondly, incorporate customers' type parameter and locational flexibility into the DRS, and based on game theory, a demand response scheme with incentive compatible constraint and participation constraint is designed to maximize the benefit both the wind power suppliers and their customers. The implication of demand response scheme is to design an incentive structure that encourages customers to sign up for the right scheme and reveal their true value of load reduction. Finally, the eight-bus system example can demonstrate the effectiveness of the proposed method.

#### **1. Introduction**

With the large-scale penetration of wind generations in power grid and the increasing load demand from customers, power systems are becoming increasingly time-varying stochastic at both demand and generation sides. Although wind generations can reduce the stress between supply and demand to some extent, their inherent volatility, uncertainty and intermittent [1] will make its quality as a power product is inferior to conventional energy and further influence the safe and economic operation of power system. The development of the power system is faced with two challenges, one is the exacerbation of issues of system security and stability caused by renewable energy integration and market competition, the other is the urgency for efficient use of energy which we must face due to the exhaustion and pollution of fossil energy. Therefore, it has become the strategy for the power system development to promote implementation of various demand response (DR) measures [2].

As an important means of demand side management (DSM), interruptible load (IL) provides an effective way to solve the above problems [3]. By signing a contract in advance, users' loads can be interrupted according to the contract during the peak periods, users can get some certain compensation

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or price discounts [4]. IL increases the reserve power of system and improved the reliability of power system, which enable it has a good prospect of application [5]. The present research of DR mainly focuses on the peak clipping, load shifting [6], reserve services [7], congestion management [8], improving power system reliability [9], increasing operating benefits [10], etc. Research on the mechanism design of DR participating in power grid operation still should be improved. In [11], an incentive-compatible mechanism is designed to encourage consumers to reveal their true type parameters, which could ensure the effective implementation of DR programs. In [12], DR compensation mechanism is constructed from the perspective of day-ahead scheduling. [13] designs a compensation mechanism in which IL is considered as the reserve power of system. [14] considers the uncertainty of distributed generation (wind power), constructs a market-based mechanism to control and coordinate the interconnection between distributed generation and power grid. All show that the critical issue is how to design DRS for the wind power suppliers and their customers to alleviate stress on the power grid through load curtailment.

Therefore, on the basis of fully analyzing and grasping the characteristics of market participants (supply side and demand side). In this paper, a rational demand response scheme (DRS) for wind integrated power system is designed which considers the interests of the demand side and generating side. Firstly, we derive the outage cost function and incentive function for different type of customers at critical locations. Therefore, the customer type parameter, as a parameter to characterize the customer performance in DRS, and the locational value parameter, as a parameter to characterize importance of critical location, are two significant variables in these studies. Then, based on game theory, a demand response scheme with incentive compatible constraint and participation constraint is designed to makes sure that the wind power supplier benefit is maximized and their customers take participate in the DRS voluntarily since they are given a satisfactory compensate fee to do so. The idea behind demand response scheme is to design an incentive structure that encourages customers to sign up for the right scheme and reveal their true value of load reduction. The eight-bus system example can illustrate the effectiveness of the proposed method.

#### 2. Demand response scheme design for wind power supplier

The outage cost of the customer to reduce their load demand depends on the curtailment amount of customers and customers' preference for curtailment. The assumption is that outage  $\cot c(\theta, x)$  of the customer  $\theta$  for curtailing *x* MW is:

$$c(\theta, x) = K_1 x^2 + K_2 x - K_2 x \theta \tag{1}$$

where  $\theta$  is used to characterize customers' preference for curtailment probabilistically, and we assume this "preference parameter"  $\theta$  possesses a uniform probability distribution  $f(\theta)$  in the interval [0,1]. It sorts the customers from the least willing to the most willing to curtail load, and let  $F(\theta) = \int_0^{\theta} f(\theta) d\theta$ .  $K_1$  and  $K_2$  are the quadratic and linear term coefficients of the outage cost function, respectively. These parameters are private customer information that is unknown to the supply-side. They are all positive, and they are estimated using the existing data. For the sake of simplicity, this paper assumes that  $K_1$ =0.5, and  $K_2$ =1 [15]. In our previous work [16-17], we give a simple example to illustrate the derivation process of the assumed values of  $K_1$ ,  $K_2$  and all the  $\theta$ .

Customer is rational enough, if the customers do not receive any compensation for their demand reduction, they will not choose to participate DR program. It means that customers will self-select the amount of demand curtailment x MW based on their monetary compensation y offered by energy supplier in order to maximize their utility naturally. The customers' benefit  $u_1(x, y, \theta)$  is defined as the amount of monetary compensation they received from energy supplier minus their outage cost due to the curtailment.

$$u_1(x, y, \theta) = y - c(x, \theta) \tag{2}$$

Wind power suppliers' benefit function  $u_2$  generated by the load curtailment of customer *j* can be expressed as

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$$u_2 = (\lambda_w + \lambda_s)x - y = \lambda x - y \tag{3}$$

where  $\lambda$  is spot market price,  $\lambda = \lambda_w + \lambda_s \cdot \lambda_w$  is the on-grid tariff of wind power.  $\lambda_s$  is the price subsidies for wind power supply per MWh provided by Chinese government in order to promote the penetration of wind generation. Usually, the electricity subsidy is 0.25-0.3 \$/kWh. Here, this article takes  $\lambda_s = 0.25$  \$/KWh.

The aim of designing DR compensation mechanism is to make optimal compensation fee scheme for a customer about some amount MW of load curtailment, so as to reduce hidden danger of security in power grid. It is actually a mathematical optimization problem, which should meet the objective of maximizing the total utility for DR. The objective function is

$$\max_{X(\lambda,Y(\lambda))} E_{\theta} u_0(X(\theta,\lambda_w),Y(X(\theta,\lambda_w)),\lambda_w)$$
(4)

Both energy supplier and customer are rational. Energy supplier will only provide compensation for customers at more critical locations due to it can reduce hidden danger of security in power grid by curtailing some amount of load. Customers will not curtail load unless there is a positive incentive for them. Thus both them subject to the individual rational constraint (IRC):

$$u_1(X(\theta,\lambda_w),Y(X(\theta,\lambda_w)),\theta) \ge 0$$
(5)

And the incentive compatibility constraint (ICC) [16].

$$u_1(X(\theta,\lambda_w),Y(\theta,\lambda_w),\theta) \ge u_1(X(\theta,\lambda_w),Y(X(\theta,\lambda_w)),\theta)$$
(6)

Constraint (6) illustrates that if a customer  $\theta_j$  reports his information  $\theta'_j$  wrongly, his benefit will not maximum, it is not wise for the customer to lie. Hence, (6) can prevent customer from lying about  $\theta$ , and it ensures customer to select their special compensation scheme according to their true willing.

Wind power suppliers can obtain the amount of voluntary reduction of load by each user through questionnaires or surveys, and determine the outage cost for each customer according to the incentive compatible contract. This maximization problem are expressed through the mechanism design and display principle using the distribution function parameterization method to obtain the contract expression of the continuous variable.

$$x(\theta) = \begin{cases} 0 & \text{if } 0 \le \theta < \frac{7}{8} - \frac{\lambda_w}{2} \\ 2\theta + \lambda_w - \frac{7}{4} & \text{if } \frac{7}{8} - \frac{\lambda_w}{2} \le \theta < 1 \end{cases}$$
(7)

$$y(\theta) = \begin{cases} 0 & if \ 0 \le \theta < \frac{1}{8} - \frac{1}{2} \\ \theta^2 - \frac{3}{2}\theta + 2\theta\lambda_w + \frac{3}{4}\lambda_w^2 - \frac{13}{8}\lambda_w + \frac{35}{64} \\ if \ \frac{7}{8} - \frac{\lambda_w}{2} \le \theta \le 1 \end{cases}$$
(8)

Therefore, the proposed mechanism design depends on the two important parameters: the local value  $\lambda_w$  and the customer preference parameter  $\theta$ .

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#### **3. Simulation Results**

The numerical experiments are carried on the eight-bus system to demonstrate the validity and effectiveness of the proposed model. The eight-bus system with 2 thermal units, 6 load notes, and 9 branches are shown in Figure 1. All the parameters can be found in [16]. We use wind units instead of thermal units. The total load capacity of the eight-bus system is 315MW, assuming that the maximum output of each wind power unit is 2.5MW, and the total amount of wind power installed in the system is 140. So the total wind output is 350MW. Due to the uncertainties and intermittency of wind power, and the impact of wind speed and geographical location, the output efficiency of wind power is hard to reach 100%, so the utilization rate of wind power is not very high. The wind power profile and the

load profile, as well as the difference between them are shown in Figure 2. The example involves three stages to illustrate the proposed optimal demand response scheme can benefit both the interests of the demand side and wind generating side.

Stage 1: Sensitivity analysis to determine the most valuable loads location

Stage 2: The Optimal DRS for wind power suppliers (WPS) and their customers (WPSC).

Stage 3: Compare the DRS for thermal energy suppliers (TES) and their customers (TESC) [15-16], as well as WPS and WPSC under different scenarios



#### 3.1. Stage 1 Analysis

The aim of sensitivity analysis is to find the most vulnerable load nodes and arranging all of them. The sensitivity of the loading margin to voltage collapse with respect to a change in each load is shown in Table 1. It can be noted that the most valuable loads buses are 7 and 8. This means that the location 7 and location 8 are the most helpful in case of wind power shortage, line congestion, voltage collapse, etc. Based on these ranks, the electrical market operation will make decision the quantitative impact of loads location information on the reliability of the system. Then electrical market operation design the specific mechanism for different location customers to curtail some amount of load when required.

#### 3.2. Stage 2 Analysis

After the relative value of all load locations is determined, another critical customer attributes, customer private information are list in Table 2. It can be seen that the bus 7 and bus 8 have the same location value (equivalent sensitivity), but have different DRS for them due to they have different customer private information. Figure 3 illustrates the optimal mechanism design. As shown in Figure 3, the customers at bus7 and at bus 8 will sign up for the different demand response scheme even though they are at equally sensitive locations. This is because the customer at bus 7 has a higher marginal cost for load reduction than the customer at bus 8.

In the following, we will discuss how do the two critical parameter ( $\lambda_w$  and  $\theta$ ) impact the design of DRS.

As shown in Table 2, the bus 4, bus 6, bus 7 and bus 8 have the same location value  $\lambda_{w} = 0.9$ . According to (7) and (8), when fix  $\lambda_{w} = 0.9$ , the formulations of load curtailment function and the compensation function as:

$$x(\theta) = \begin{cases} 0 & 0 \le \theta < 0.425\\ 2\theta - 0.85 & 0.425 \le \theta \le 1 \end{cases}$$
(9)

$$y(\theta) = \begin{cases} 0 & 0 \le \theta < 0.425\\ \theta^2 + 0.3\theta - 0.308125 & 0.425 \le \theta \le 1 \end{cases}$$
(10)





Both the load curtailment  $x(\theta)$  and the compensation fee  $y(\theta)$  are the function of the customer preference parameter  $\theta$ . Figure 4 design the specific DRS for customers with the locational value  $\lambda_w = 0.9$ . Figure 5 shows that the number of customers participating DR project varies with the value of  $\lambda_w$ .

The role of the customer preference parameter  $\theta$  is obvious, because it determines the type of customer (which in turn determines the cost of their load curtailment). However, the role of local value  $\lambda_w$  may be subtle. Since the local value  $\lambda_w$  is a parameters of economic analysis from engineering, which indicates that the customer's location is one of the most important aspects to design the optimal DRS. Some locations will be more expensive to transmit electricity than others. It makes sense for electricity market operation to design the specific DRS for customers at expensive locations.

Figure 6 shows the customer' benefit of WPSC and TESC in bus 4 and bus 6, respectively. Their true preference parameter  $\theta = 0.8$ , and locational value  $\lambda_w = 0.9$ . As shown in Figure 6, obviously, only

the user report his true value, his interest is the biggest of all. According to the formula (9) and (10), the calculation:

Load curtailment:  $x(\theta) = 7.50$ MW; Compensation fee:  $y(\theta) = $5718.75$ ; Customers' benefit:  $V_1(\theta, x, y) = $1406.25$ .

Customer is rational, in order to obtain more compensation fee, he may lie. If the customer with his true value  $\theta = 0.8$  sign up the scheme for the customer with  $\theta = 0.9$ , then their contract will be:

Load curtailment:  $x(\theta) = 9.50$ MW ; Compensation fee:  $y(\theta) = $7718.75$  ; Customers' benefit:  $V_1(\theta, x, y) = $1306.25$ .

It is easy to find out that the benefit of the customer who lies is reduced, so the customer is best to tell their true value and sign up for a scheme that is specifically designed for him.

In addition, compare with the DRS for TES and TESC, the DRS for WPS and WPSC not only increase the benefit both WPS and their customers, but also encourages more customers to sign up for the right scheme and reveal their true value of load reduction. All the merits improve the utilization efficiency of wind power and promote the accommodation of wind generation.

According to (7) and (8), take bus 2 as an example, when fix  $\lambda_{w} = 0.4$ , the formulations of load curtailment function and the compensation function as:

$$x(\theta) = \begin{cases} 0 & 0 \le \theta < 0.425\\ 2\theta - 0.85 & 0.425 \le \theta \le 1 \end{cases}$$
(11)

$$y(\theta) = \begin{cases} 0 & 0 \le \theta < 0.425\\ \theta^2 + 0.3\theta - 0.308125 & 0.425 \le \theta \le 1 \end{cases}$$
(12)

As mentioned above, the different customers have different preference parameter  $\theta$ . The sensitivity is also different at different load location. Thus the amount of load curtailment and compensation fee are different. As shown in Figure 7, the thermal energy suppliers' customer signing up for the DRS at bus 2 will not benefit. Their benefit is zero or negative according to formula (11) and (12). However, if the wind power suppliers' customers to sign up for the DRS, the customers in the range of  $\theta \in [0.675, 0.925]$  can still benefit. The benefit of customers at bus 2 and interval of  $\theta \in [0,0.675]$  is zero, and it is negative in the interval of  $\theta \in [0.925,1]$ . Through the comparison analysis, wind power suppliers provide a DRS for the customers at the more expensive location, it also can make some customers benefit. This illustrates that the DRS for wind power suppliers has more extensively applicable scope, which may bring more benefits to customers. On the on hand, it encourage more customer to sign up for the right scheme and reveal their true value of load reduction. On the other hand, it promotes the accommodation of high penetration of wind generation, which achieves a winwin result.

Table 3 lists the optimal DRS results for wind and thermal power.

Table 3. A optimal result of DRS.				<b>Table 4.</b> Non-optimal result of DRS when fix $\lambda = 0.7$ .					
<u> </u>	Thermal		Wind generation		Custom	Thermal		Wind generation	
Custome	$\frac{\mathrm{d} \mathbf{x}(\theta)}{\mathrm{(MW)}}$	$y(\theta)/(\$)$	$x(\theta)/(MW)$	$y(\theta)/(\$)$	er	$x(\theta)/(MW)$	$y(\theta)/(\$)$	$x(\theta)/(MW)$	$y(\theta)/(\$)$
Bus 2	0.00	0.00	0.5	168.75					
Bus 4	5.0	2875	7.5	5718.75	Bus 2	1.00	375.00	3.5	1968.75
Bus 5	2.00	900	4.5	2868.75	Bus 4	3.00	1275.00	5.5	3368.75
Bus 6	5.00	2875	7.5	5718.75	Bus 5	1.00	375.00	3.5	1968.75
Bus 7	0.00	0.00	1.5	918.75	Bus 6	3.00	1275.00	5.5	3368.75
Bus 8	7.00	4375	9.5	7718.75	Bus 7	0.00	0.00	0.00	0.00
Optimal Load Relief=19 MW Optimal Load Relief=31 MW			Bus 8	5.00	2375.00	7.5	4968.75		
Increase in Margin=24.34 MWIncrease in Margin=29.86 MW				Optimal Load Relief=13 MW			Optimal Load Relief=25.5 MW		
				Increase in Margin=15.91 MW			Increase in Margin=21.035 MW		

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As shown in Table 3, under the same DRS mechanism, the penetration of wind generation integrated into power grid increase the amount of customers participating in demand response projects. The amount of load curtailment has increased by 38.7%, and the load margin increased by 18.5%. Which will improve the safety margin of the system and alleviate the pressure of transmission line more effectively during the peak and the failure period, thus improve the safety level of the system.

## 3.3. Stage 3 Analysis

In order to emphasize the importance of the two parameters: The local value  $\lambda_w$  and the customer preference parameter  $\theta$ . Table 4 gives the non-optimal results of DRS for WPSC and TESC when fixed  $\lambda_w = 0.7$ , respectively. It can be seen that the amount of load curtailment for WPSC is more than it for TESC, and the result is also a smaller increase in the loading margin (LM).

Table 5 gives the non-optimal results of DRS for WPSC and TESC when fixed  $\theta = 0.7$ , respectively. It can be seen that the amount of load curtailment for WPSC is more than it for TESC, and the result is also a smaller increase in the LM. The DRS for WPSC has an obvious advantage in terms of both the amount of load curtailment and the increase in load margins better than DRS for TESC.

<b>Table 5.</b> Non-optimal result of DRS when fix $\theta = 0.7$ .						
Constants	Thermal		Wind generation			
Customer	$x(\theta)/(MW)$	$y(\theta)/(\$)$	$x(\theta)/(MW)$	$y(\theta)/(\$)$		
Bus 2	0.00	0.00	0.5MW	168.75		
Bus 4	3.00	1575.00	5.5MW	391 8.75		
Bus 5	2.00	900.00	4.5MW	2868.75		
Bus 6	3.00	1575.00	5.5MW	391 8.75		
Bus 7	3.00	1575.00	5.5MW	391 8.75		
Bus 8	3.00	1575.00	5.5MW	391 8.75		
Optimal L	oad Relief=	14MW	Optimal Load Relief=27MW			
Increase in	n Margin=14	4.73MW	Increase in Margin=27.12 MW			

We carry on the comprehensive comparison to the three scenarios, as shown in Table 6. It is concluded that only when the optimal DRS enables the WPS, TES and WPSC, TESC to get maximum benefit. Namely, only the customer tell their true private information and sign up for the specific DRS, their benefit is the most. The amount of load curtailment is most and the load margin increase is also the largest. Which reduces transmission line overload, ensure the safety of the system, thus avoid the occurrence of accidental events such as voltage collapse. It also proves the absolute advantage of the penetration of wind power.

Table 6. The Comparison results under different scenarios.							
	Scenarios	C(MW)	LM(MW)	SP(\$)	CP(\$)		
	Optimal	19	24.34	5875.00	2775.00		
Thermal	$\lambda_w = 0.7$	13	15.91	3425.00	1125.00		
	$\theta = 0.7$	14	14.73	5200.00	1000.00		
	Optimal	31	29.86	11837.5	12387.5		
Wind	$\lambda_w = 0.7$	25.5	21.035	10181.25	3531.25		
	$\theta = 0.7$	27	27.12	11637.5	8887.5		

### 4. Conclusions

This paper proposes a demand response scheme for wind integrated power system based on mechanism design theory. Under the scenario of power shortage, we carry on the compare the DRS for WPSC with TESC. In the perspective of utility theory, the DRS for wind power suppliers has more extensively applicable scope, which may bring more benefits to customers. On the on hand, it

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encourage more customer to sign up for the right scheme and reveal their true value of load reduction. On the other hand, it promotes the accommodation of high penetration of wind generation. In addition, the government subsidy policy for wind power supplier, further increase the utilization efficiency of wind power, which achieve a win-win result. From the perspective of stable and reliable operation of the system. During peak periods, when the system is suffering from peak load or emergencies, customers can curtail the load actively or controllably according the DRS' requirements to alleviate the stress brought on the system by events and contingencies.

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