Vickrey-Clark-Groves-based Method for Eradicating Deceptive Behaviors in Demand Response Transactions

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***Abstract*—Demand response transactions between electric consumers, load aggregators, and the distribution network manager based on the "combination of price and incentive" are feasible and efficient. However, the incentive payment of demand response is quantified based on private information, which gives the electric consumers and load aggregators the possibility of defrauding illegitimate interests by declaring false information. This paper proposes a method based on Vickrey-Clark-Groves (VCG) theory to prevent electric consumers and load aggregators from taking illegitimate interests through deceptive declaration in the demand response transactions. Firstly, a demand response transaction framework with the price-and-incentive combined mode is established to illustrate the deceptive behavior in the demand response transaction. Then, the idea for eradicating deceptive declarations based on VCG theory is given, and a detailed VCG-based mathematical model is constructed following the demand response transaction framework. Further, the proofs of incentive compatibility, individual rationality, cost minimization, and budget balance of the proposed VCG-based method are given. Finally, a modified IEEE 33-node system and a modified IEEE 123-node system are used to illustrate and validate the proposed method.**

***Index Terms*—Demand response, transaction, incentive mode, cost-sharing, false information, deceptive behavior.**

I. Introduction

CLIMATE changes and environmental politics have become increasingly entrenched [1], [2]. Reducing carbon emissions and developing clean energy have successively become the primary objectives of energy development in most countries [3], [4]. As the proportion of renewable energy in primary energy rises, the power system, as one of the primary energy consumers, is also evolving in properties [5], [6]. Due to the climate relevance and the unpredictability of renewable energy sources, their large-scale integration significantly impacts the power system operation.

In this context, demand response (DR) is utilized as a powerful tool to counteract the random effects of renewable energy sources and improve operational stability and economy [7], [8]. Regarding the choice of DR mechanism, there are two main kinds. One is the price-based DR, which adjusts prices to guide users to participate in DR [9]-[11]. This mechanism is based on longer scale control intervals yet cannot respond promptly to short-term peak load. The other is the incentive-based DR, which motivates users to change their electricity consumption by the contract [12], [13]. While this mechanism could cope with short-term peak loads, it could only be applied to some specific types of loads. Thus, in our previous work [14], a combination of price and incentive mechanisms is proposed, allowing the strengths of the both. It can compensate for the lack of flexibility in incentive-based DR, and increase the willingness of loads to respond compared with price-based DR.

Typically, the benefits for responders come from two sources. One is the electricity tariff savings, and the other is the incentive payments. The former is related to the real-time price, and the latter is related to the response cost of the responders [15]. However, due to the privacy protection of the seller in the DR transaction, the actual response cost data are only available to the responders. As a result, responders could declare inflated costs to obtain higher incentive payments, defined as a deceptive declaration in this paper. There is already some similar literature on this topic. In [16], the inconvenience function of each consumer (which is used for load curtailment) is captured by a type value, and the value may be deceptively declared. In [17], the loss of reference price in the fixed proportion model leads to deceptive behaviors of speculators in this model. In [18], mixed-use buildings that deceptively declare in a bidding game in the emergency DR program are discussed. A deceptive declaration problem could lead to severe consequences in a healthy market. For the development of the market, the illegitimate profit obtained by the deceiver undermines the interests of other honest participants, leading to the potential loss of economic efficiency. Further, more participants will engage in deceptive behavior, squeezing the market share of honest traders and resulting in a market collapse [19].

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There is no doubt that the deceptive declaration must be tackled. In electricity markets, mechanism design could get to the root of the deceptive problem, among which the Vickery [20]-Clarke [21]-Groves [22] (VCG) theory is widely adopted [23]. VCG is a pricing mechanism to elicit truthful information by structuring payment from users' information [24]. In [25], the VCG theory is applied to managing the two-sided nature of local energy markets to address the budget-balance problem. In [26], the VCG mechanism minimizes the total cost at a truth-telling dominant strategy equilibrium. In [27], the VCG-based core-selecting mechanism is proposed to address the coalition issues. In [28], the VCG mechanism is applied in a two-stage stochastic electricity market to achieve incentive compatibility by rewarding market participants for their contribution. Several studies have demonstrated that the VCG mechanism could achieve truth-telling in the existing literature. However, few studies focus on applying the VCG mechanism in the DR trading model.

This motivates us to apply the VCG theory to eradicate deceptive behaviors in price-and-incentive combined DR transactions. The contributions of this paper are as follows.

1) To improve the fairness and efficiency of the transaction market, a DR transaction framework with a VCG-based cost-sharing method is established to eradicate the deceptive declaration problem.

2) To provide a theoretical basis for the DR, considering deceptive behaviors, a cost-sharing DR transaction model is incrementally deduced from the price-based model under the DR transaction framework.

3) To accommodate the DR transaction framework, considering the deceptive declaration from two different subjects, an extended double-nested VCG-based method is applied for the DR model. Furthermore, the validity of the proposed method is mathematically demonstrated.

The rest of this paper is organized as follows. In Section II, the deceptive declaration problem is formulated. The idea of eliminating deceptive behaviors based on VCG theory is given in Section III. The mathematical formulation is presented in Section IV. Proofs of the proposed method are deduced in Section V. The case study is provided in Section VI. Finally, Section VII concludes this paper.

II. Deceptive Declaration Problem Formulation

This section introduces the traditional price-based DR transaction framework, followed by an incentive-based model of DR trading, which proposes a "cost-sharing" incentive method. Further, the cost-sharing DR model considering deceptive behaviors is presented. It is worth pointing out that the models in this section are abstract, and the corresponding detailed mathematical models can be found in Section III.

In the DR transaction, there are three types of subjects: ① electric customer (EC), which is a consumer of electrical energy and maximizes the economic benefit of participating in DR while ensuring the minimum electricity consumption satisfaction decline; ② load aggregator (LA), which has an EC-owned service agency and maximizes its economic benefit by the transaction with distribution network manager (DNM) to earn service spreads; ③ DNM, which is a power system operator and minimizes the grid operation cost by purchasing DR services. It is essential to clarify that the EC focus of this paper is the general definition of electrical load rather than a specific type of load.

Figure 1 illustrates the DR transaction framework.

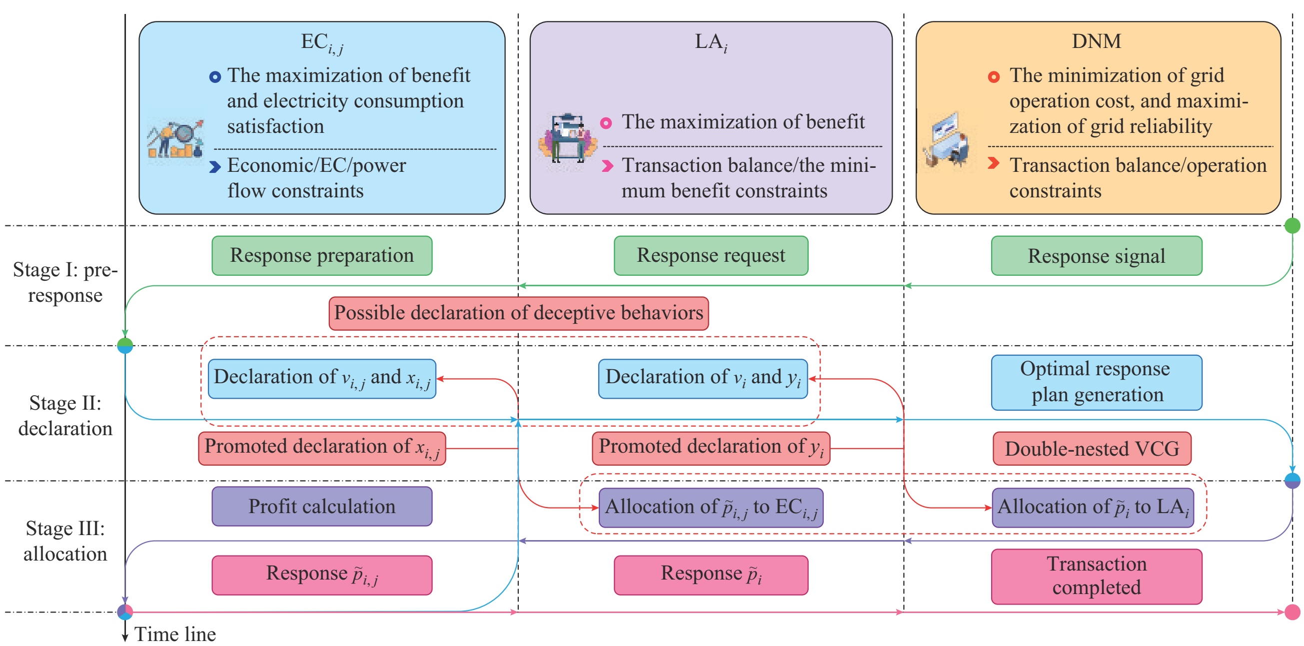

Fig. 1. DR transaction framework.

After receiving the response signal issued by DNM, LAs send the instructions to their ECs. Then, EC declares its response price $v_{i,j}$ and a parameter related to response cost $\tilde{x}_{i,j}$ to LAs. Then, LAs reconsolidate the two declared parameters into v_i and $\tilde{x}_i$ and declare them to DNM. Next, DNM generates the optimal response volume $\tilde{p}_i$ to each LA according to the declared parameters. LA then allocates response volume $\tilde{p}_{i,j}$ to each EC based on its assigned $\tilde{p}_i$. Finally, if $\tilde{p}_{i,j}$ is accepted by the ECs, the corresponding response plan will be executed, and the expenses incurred in the DR transactions will be cleared sequentially. Otherwise, the "declare parameters-generate plan" process will be repeated until the conditions are satisfied. The whole process of DR can be regarded as a double-nested transaction model.

Defining that there exist i LAs in the power system and j ECs agented by per LA, the transaction optimization models for each of the three subjects mentioned above are as follows.

A. Price-based DR Transaction Framework

The price-based DR transaction framework is summarized as following models.

1) Price-based DR Model of EC

The objective function of $EC_{i,j}$ contains two parts: tariff savings and response cost [29]. The objective function of $EC_{i,j}$ is generally considered as:

$$\pi_{i,j}=\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right)-\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right) \tag{1}$$

where $\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right)$ is the economic benefit of $EC_{i,j}$ from the participation in DR; $\boldsymbol{V}_i=\left[v_{i,1},v_{i,2},...,v_{i,j},...,v_{i,j_{\max}}\right]^{\mathrm{T}}$ is the vector of response prices declared by ECs; $\boldsymbol{P}_i=\left[P_{i,1},P_{i,2},...,P_{i,j},...,P_{i,j_{\max}}\right]^{\mathrm{T}}$ is the vector of actual power response volume for ECs; $\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right)$ is the economic cost for $EC_{i,j}$ to participate in DR; and $\boldsymbol{X}_i=\left[x_{i,1},x_{i,2},...,x_{i,j},...,x_{i,j_{\max}}\right]^{\mathrm{T}}$ is the vector of key parameters in $\varphi_{i,j}\left(\boldsymbol{X}_i\right)$.

After considering the power balance and rational bidding constraints, the basic priced-based DR model of EC is formed. In the discussion below, $h(\cdot)=0$ represents equality constraints, and $g(\cdot)\le 0$ represents inequality constraints.

$$\begin{cases}\max\limits_{v_{i,j}}\left(\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right)-\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right)\right)\\ \text{s.t. } h\left(\boldsymbol{P}_i\right)=0\\ \qquad g\left(\boldsymbol{V}_i\right)\le 0\end{cases} \tag{2}$$

2) Price-based Model of LA

The objective function of LA_i contains two parts: the service revenue received from DNM, and the tariff losses from ECs. The objective function of LA_i is generally considered as (3).

$$\rho_i=\kappa_i\left(\boldsymbol{W},\boldsymbol{P}\right)-\sum_{j=1}\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right) \tag{3}$$

where $\kappa_i\left(\boldsymbol{W},\boldsymbol{P}\right)$ is the service revenue received by LA_i from DNM; $\boldsymbol{W}=\left[w_1,w_2,...,w_i,...,w_{i,\max}\right]^{\mathrm{T}}$ is the vector of response prices declared by LAs; and $\boldsymbol{P}=\left[P_1,P_2,...,P_i,...,P_{i,\max}\right]^{\mathrm{T}}$ is the vector of actual power response volume for LAs.

Similarly, constraints are considered, and the priced-based transaction model for LA_i is constructed.

$$\begin{cases}\max\limits_{w_i,P_{i,j}}\left(\kappa_i\left(\boldsymbol{W},\boldsymbol{P}\right)-\sum\limits_{j=1}\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right)\right)\\ \text{s.t. } h\left(\boldsymbol{P},\boldsymbol{P}_i\right)=0\\ \qquad g\left(\boldsymbol{W}\right)\le 0\end{cases} \tag{4}$$

3) Price-based Model of DNM

The objective function of DNM only contains the service cost paid to LAs. After adding constraints, the price-based transaction model of DN is constructed as (5).

$$\begin{cases}\min\limits_{P_i}\sum\limits_{i=1}-\kappa_i\left(\boldsymbol{W},\boldsymbol{P}\right)\\ \text{s.t. } h\left(\boldsymbol{P}\right)=0\\ \qquad g\left(\boldsymbol{P}\right)\le 0\end{cases} \tag{5}$$

B. Cost-sharing DR Transaction Model

Many studies have shown that price-based DR is not practical. Thus, the incentive-based DR is applied in parallel to increase participants' response willingness [30]. Further, the cost-sharing DR model is proposed based on the coupled DR.

1) Cost-sharing Model of EC

If solely relying on regular tariffs, the willingness of ECs to participate in DR is typically limited. In order to increase the willingness of ECs to participate in DR, an extra reward has to be paid to ECs, as given in (6).

$$\pi'_{i,j}=\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right)-\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right)+\lambda'_{i,j}\left(\boldsymbol{P}_i\right) \tag{6}$$

where $\lambda'_{i,j}\left(\boldsymbol{P}_i\right)>0$ is the additional benefit.

The additional benefit is associated with the cost of $EC_{i,j}$. Thus, $\lambda'_{i,j}\left(\boldsymbol{P}_i\right)=a\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right)$, where a is the cost-sharing coefficient [14]. Accordingly, (6) can be transformed into (7).

$$\pi''_{i,j}=\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right)-(1-a)\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right) \tag{7}$$

With the introduction of this mechanism, when participating in DR transactions, in addition to reporting their response prices, ECs need to declare the response costs. We assume the response cost function is the same for all ECs, with only the critical variable $x_{i,j}$.

Then, the cost-sharing model of $EC_{i,j}$ is:

$$\begin{cases}\max\limits_{v_{i,j}}\left[\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right)-(1-a)\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right)\right]\\ \text{s.t. } h\left(\boldsymbol{P}_i\right)=0\\ \qquad g\left(\boldsymbol{V}_i\right)\le 0\end{cases} \tag{8}$$

2) Cost-sharing Model of LA

LA bears the additional benefit paid to ECs. However, this additional expenditure could seriously influence the benefit of LA. To offset this cost, LA may continue to share this cost with the higher level, i.e., DNM.

According to (8), (3) can be deformed as:

$$\rho'_i=\kappa_i\left(\boldsymbol{W},\boldsymbol{P}\right)-\sum_{j=1}\lambda_{i,j}\left(\boldsymbol{V}_i,\boldsymbol{P}_i\right)-\sum_{j=1}a\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right) \tag{9}$$

According to the cost-sharing model mentioned above, the cost received by LA_i from DNM is related to its response cost function and power response volume. As LA does not have a response cost function, the response cost function declared by LA_i should be consistent with the function declared by $EC_{i,j}$. Let $\bar{\varphi}_i(\boldsymbol{Y})$ be the response cost function of LA_i, then $\bar{\varphi}_i(y_i)=\sum_{j=1}\omega_{i,j}\varphi_{i,j}(x_{i,j})\Big/\sum_{j=1}1$, where $\omega_{i,j}$ is the weight factor. Therefore, (9) is formulated into (10).

$$\rho_i''=\kappa_i(\boldsymbol{W},\boldsymbol{P})-\sum_{j=1}\lambda_{i,j}(\boldsymbol{V}_i,\boldsymbol{P}_i)-\sum_{j=1}a\varphi_{i,j}(\boldsymbol{X}_i,\boldsymbol{P}_i)+b\bar{\varphi}_i(\boldsymbol{Y},\boldsymbol{P}) \tag{10}$$

where b is the cost-sharing coefficient.

Similar to $EC_{i,j}$, the cost-sharing model of LA_i is:

$$\begin{cases}\max\limits_{w_i,P_{i,j}}\left(\kappa_i(\boldsymbol{W},\boldsymbol{P})-\sum_{j=1}\lambda_{i,j}(\boldsymbol{V}_i,\boldsymbol{P}_i)-\sum_{j=1}a\varphi_{i,j}(\boldsymbol{X}_i,\boldsymbol{P}_i)+b\bar{\varphi}_i(\boldsymbol{Y},\boldsymbol{P})\right)\\ \text{s.t. } h(\boldsymbol{P},\boldsymbol{P}_i)=0\\ \quad g(\boldsymbol{W})\le 0\end{cases} \tag{11}$$

3) Cost-sharing Model of DNM

Throughout the transaction, a portion of reduced electricity consumption satisfaction cost of ECs is eventually transferred to the DNM. Then, DNM needs to pay more to get better response results. Thus, we have:

$$\begin{cases}\min\limits_{P_i}\sum_{i=1}\left(-\kappa_i(\boldsymbol{W},\boldsymbol{P})-b\bar{\varphi}_i(\boldsymbol{Y},\boldsymbol{P})\right)\\ \text{s.t. } h(\boldsymbol{P})=0\\ \quad g(\boldsymbol{P})\le 0\end{cases} \tag{12}$$

C. Cost-sharing DR Transaction Framework Considering Deceptive Behaviors

The cost-sharing model in Section II-B is in an ideal situation. In practice, due to the inequality and privacy of information, for the LA_i, the actual response cost function of the $EC_{i,j}$ is unknown. Only the response cost function declared by the EC can be obtained, which leads to the possibility of deceptive behaviors.

1) Deceptive Behavior of EC

The response cost declared by $EC_{i,j}$ would generally be higher than its true response cost, i.e., $\varphi_{i,j}(\tilde{\boldsymbol{X}}_i)\ge\varphi_{i,j}(\boldsymbol{X}_i)$, for obtaining more benefit. Then, (7) can be transformed into:

$$\pi_{i,j}'''=\lambda_{i,j}(\boldsymbol{V}_i,\tilde{\boldsymbol{P}}_i)+a\varphi_{i,j}(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i)-\varphi_{i,j}(\boldsymbol{X}_i,\boldsymbol{P}_i) \tag{13}$$

where $\tilde{\boldsymbol{X}}_i=\left[\tilde{x}_{i,1},\tilde{x}_{i,2},\dots,\tilde{x}_{i,j},\dots\right]^{\mathrm{T}}$ is the vector of crucial parameter for the response cost declared by $EC_{i,j}$; and $\tilde{\boldsymbol{P}}_i$ is the optimal responsive plan of the system when $EC_{i,j}$ declares $\varphi_{i,j}(\tilde{\boldsymbol{X}}_i)$.

Assuming that the response cost function is quadratic [31] and the critical parameter is the primary term coefficient. The illegitimate profit that $EC_{i,j}$ obtains by the deceptive declaration can be represented by the discrepancy between the area of the red-shaded part and the blue-shaded part in Fig. 2. Clearly, this interpolation is positive.

From the perspectives of $EC_{i,j}$, it undoubtedly expects to maximize the interest, then (8) can be transformed into (14). Another decision variable, i.e., a key parameter of response cost $\tilde{x}_{i,j}$, emerges.

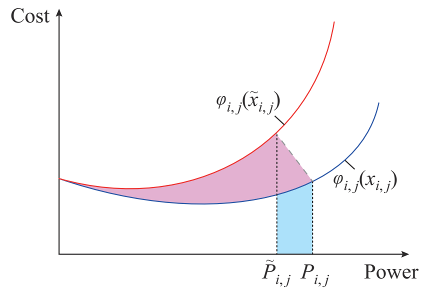

Fig. 2. Illegitimate profit from deceptive declaration.

$$\begin{cases}\max\limits_{v_{i,j},\tilde{x}_{i,j}}\left(\lambda_{i,j}(\boldsymbol{V}_i,\tilde{\boldsymbol{P}}_i)+a\varphi_{i,j}(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i)-\varphi_{i,j}(\boldsymbol{X}_i,\boldsymbol{P}_i)\right)\\ \text{s.t. } h(\tilde{\boldsymbol{P}}_i)=0\\ \quad g(\boldsymbol{V}_i)\le 0\\ \quad g(\tilde{\boldsymbol{X}}_i)\le 0\end{cases} \tag{14}$$

2) Deceptive Behavior of LA

In the case of deceptive declarations by ECs, LAs will suffer if they are honest. Furthermore, from another part, DNM also could not acquire the response cost function of LAs. With this combination of factors, LAs are equally likely to make deceptive declarations, as described in (15).

$$\rho_i'''=\kappa_i(\boldsymbol{W},\tilde{\boldsymbol{P}})-\sum_{j=1}\lambda_{i,j}(\boldsymbol{V}_i,\tilde{\boldsymbol{P}}_i)-\sum_{j=1}a\varphi_{i,j}(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i)+b\bar{\varphi}_i(\tilde{\boldsymbol{Y}},\tilde{\boldsymbol{P}}) \tag{15}$$

Therefore, LA_i can be described by (16) with an additional decision variable $\tilde{y}_i$.

$$\begin{cases}\max\limits_{w_i,\tilde{y}_i,P_{i,j}}\left(\kappa_i(\boldsymbol{W},\tilde{\boldsymbol{P}})-\sum_{j=1}\lambda_{i,j}(\boldsymbol{V}_i,\tilde{\boldsymbol{P}}_i)-\sum_{j=1}a\varphi_{i,j}(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i)+b\bar{\varphi}_i(\tilde{\boldsymbol{Y}},\tilde{\boldsymbol{P}})\right)\\ \text{s.t. } h(\tilde{\boldsymbol{P}},\tilde{\boldsymbol{P}}_i)=0\\ \quad g(\boldsymbol{W})\le 0\\ \quad g(\tilde{\boldsymbol{Y}})\le 0\end{cases} \tag{16}$$

3) Model of DNM

Since the bidding strategies of the other two stakeholders involved in the market have changed, the model of DNM can be described as:

$$\begin{cases}\min\limits_{P_i}\sum_{i=1}\left(-\kappa_i(\boldsymbol{W},\tilde{\boldsymbol{P}})-b\bar{\varphi}_i(\boldsymbol{Y},\tilde{\boldsymbol{P}})\right)\\ \text{s.t. } h(\tilde{\boldsymbol{P}})=0\\ \quad g(\tilde{\boldsymbol{P}})\le 0\end{cases} \tag{17}$$

In this subsection, the abstract model of a price-based three-subject DR transaction is first summarized. Further, the cost-sharing DR model is proposed to increase the willingness of responders. Deceptive behaviors are considered due to the realistic information inequity in the last part.

III. Idea of Eliminating Deceptive Behaviors Based on VCG Theory

In the previous section, the cost-sharing DR transaction model is established to describe the deceptive behaviors of ECs and LAs. In order to maintain market fairness, deceptive behaviors should be eradicated from the market.

To eradicate deceptive behaviors, illegitimate profits gained by deceptive declarations should be minimized. This target should be considered in the mechanism design session and is reflected in the objective functions.

For $\text{EC}_{i,j}$:

$$\begin{cases}\max\limits_{v_{i,j},\tilde{x}_{i,j}}\left(\lambda_{i,j}\left(\boldsymbol{V}_i,\tilde{\boldsymbol{P}}_i\right)+\min\left(a\varphi_{i,j}\left(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i\right)-\varphi_{i,j}\left(\boldsymbol{X}_i,\tilde{\boldsymbol{P}}_i\right)\right)\right)\\ \text{s.t. }\ h\left(\tilde{\boldsymbol{P}}_i\right)=0\\ \qquad g\left(\boldsymbol{V}_i\right)\le 0\\ \qquad g\left(\tilde{\boldsymbol{X}}_i\right)\le 0\end{cases} \tag{18}$$

For LA_i:

$$\begin{cases}\max\limits_{w_i,\tilde{y}_i,P_{i,j}}\left(\kappa_i\left(\boldsymbol{W},\tilde{\boldsymbol{P}}\right)-\sum\limits_{j=1}\lambda_{i,j}\left(\boldsymbol{V}_i,\tilde{\boldsymbol{P}}_i\right)-\right.\\ \qquad\left.\sum\limits_{j=1}a\varphi_{i,j}\left(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i\right)+\min\left|b\bar{\varphi}_i\left(\tilde{\boldsymbol{Y}},\tilde{\boldsymbol{P}}\right)\right|\right)\\ \text{s.t. }\ h\left(\tilde{\boldsymbol{P}},\tilde{\boldsymbol{P}}_i\right)=0\\ \qquad g\left(\boldsymbol{W}\right)\le 0\\ \qquad g\left(\tilde{\boldsymbol{Y}}\right)\le 0\end{cases} \tag{19}$$

In this paper, to solve the deceptive declaration in the transaction, an incentive payment mechanism based on the VCG is introduced to facilitate the actual declaration of response cost of transaction participants [32].

As the proposed DR transaction model is a double-nest transaction model, an extended double-nested VCG-based incentive allocation mechanism is applied to accommodate the DR model.

For $\text{EC}_{i,j}$, the additional benefit is determined by the declared response cost function and the substitution effect of other ECs.

$$\lambda'_{i,j}=a\left[\sum_{j'\ne j,j'=1}\varphi_{i,j'}^{-j}\left(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i\right)-\left(\sum_{j=1}\varphi_{i,j}\left(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i\right)-\varphi_{i,j}\left(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i\right)\right)\right] \tag{20}$$

where $\varphi_{i,j'}^{-j}$ is the cost function for the remaining ECs to redeclare after excluding EC_j. With this allocation strategy, we have:

$$\varphi_{i,j}\left(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i\right)\le\varphi_{i,j}\left(\boldsymbol{X}_i,\boldsymbol{P}_i\right) \tag{21}$$

$$\min\left|a\varphi_{i,j}\left(\tilde{\boldsymbol{X}}_i,\tilde{\boldsymbol{P}}_i\right)-\varphi_{i,j}\left(\boldsymbol{X}_i,\tilde{\boldsymbol{P}}_i\right)\right|=0 \tag{22}$$

Similarly, for LA_i, we can obtain:

$$\kappa'_i=b\left[\sum_{i'\ne i,i'=1}\bar{\varphi}_{i'}^{-i}\left(\tilde{\boldsymbol{Y}},\tilde{\boldsymbol{P}}\right)-\left(\sum_{i=1}\bar{\varphi}_i\left(\tilde{\boldsymbol{Y}},\tilde{\boldsymbol{P}}\right)-\bar{\varphi}_i\left(\tilde{\boldsymbol{Y}},\tilde{\boldsymbol{P}}\right)\right)\right] \tag{23}$$

$$\min\left|b\bar{\varphi}_i\left(\tilde{\boldsymbol{Y}},\tilde{\boldsymbol{P}}\right)\right|=b\bar{\varphi}_i\left(\boldsymbol{Y},\boldsymbol{P}\right) \tag{24}$$

Adequate mathematical demonstrations of incentive compatibility, individual rationality, cost minimization, and budget balance of the proposed mechanism are given in Section V [33].

This section eradicates deceptive behaviors in the DR transaction process by applying the VCG-based method and analyses why this mechanism achieves effectiveness from the perspective of the objective functions.

IV. Mathematical Formulation

The DR transaction may happen during multiple periods, so we add a subscript t defined as time. Further, define the benefit and cost of the three stakeholders as B and C, respectively, for precise elaborations. For example, $B_{i,j,t}^{\pi'''}$ represents the benefit of $\text{EC}_{i,j}$ participating in the transaction at time t.

A. DR Transaction Model of Stakeholders

1) Model of EC

The objective function of $\text{EC}_{i,j}$ to participate in the DR transaction can be expressed as (25). It includes three parts, as shown in (26).

$$\max\sum_{t=1}B_{i,j,t}^{\pi'''} \tag{25}$$

$$B_{i,j,t}^{\pi'''}=B_{i,j,t}^{\lambda}+B_{i,j,t}^{\lambda'}-C_{i,j,t}^{\varphi} \tag{26}$$

where $B_{i,j,t}^{\lambda}$ is the benefit of $\text{EC}_{i,j}$ for participating in DR; $B_{i,j,t}^{\lambda'}$ is the additional incentive benefit from LA_i (refer to Section IV-B); and $C_{i,j,t}^{\varphi}$ is the equivalent economic cost of $\text{EC}_{i,j}$ due to electricity consumption satisfaction decline for participating in DR. Superscript π''' denotes the abstract model of π''' in Section II, λ denotes the abstract model of λ in Section II, and vice versa.

After the DR transaction, the benefit $B_{i,j,t}^{\lambda}$ obtained by $\text{EC}_{i,j}$ can be expressed as:

$$B_{i,j,t}^{\lambda}=v_{i,j,t}P_{i,j,t}^{sell} \tag{27}$$

where $v_{i,j,t}$ is the power price declared to LA_i by $\text{EC}_{i,j}$; and $P_{i,j,t}^{sell}$ is the responsive power volume sold by $\text{EC}_{i,j}$ to LA_i.

$C_{i,j,t}^{\varphi}$ involves two items, i.e., the equivalent economic cost of electricity consumption mode satisfaction (ECMS) [34] and electricity consumption cost satisfaction (ECCS) [35] decline, which can be calculated by (28) and (29). The indexes for evaluating the ECMS and ECCS, represented by $\chi_{i,j,t}^{ECMS}$ and $\chi_{i,j,t}^{ECCS}$, are shown as (30) and (31), respectively.

$$C_{i,j,t}^{\varphi}=C_{i,j,t}^{ECMS}+C_{i,j,t}^{ECCS} \tag{28}$$

$$\begin{cases}C_{i,j,t}^{ECMS}=k_{i,j,t}^{ECMS}\left(1-\chi_{i,j,t}^{ECMS}\right)\\ C_{i,j,t}^{ECCS}=k_{i,j,t}^{ECCS}\left(1-\chi_{i,j,t}^{ECCS}\right)\end{cases} \tag{29}$$

$$\chi_{i,j,t}^{ECMS}=\frac{\left(\delta_{i,j,t}^{ECMS}\right)^2}{\theta_{i,j,t}^{ECMS}}\left(1-\frac{P_{i,j,t}^{sell}}{P_{i,j,t}^{0}}\right)-\frac{\left(\delta_{i,j,t}^{ECMS}\right)^2}{2\theta_{i,j,t}^{ECMS}}\left(1-\frac{P_{i,j,t}^{sell}}{P_{i,j,t}^{0}}\right)^2 \tag{30}$$

$$\chi_{i,j,t}^{ECCS}=1-\frac{v_{i,j,t}\left(P_{i,j,t}^{0}-P_{i,j,t}^{sell}\right)-v_{0,t}P_{i,j,t}^{0}}{v_{0,t}P_{i,j,t}^{0}} \tag{31}$$

where $k_{i,j,t}^{ECMS}$ and $k_{i,j,t}^{ECCS}$ are the parameters for calculating the equivalent economic cost of ECMS and ECCS decline, respectively; $\delta_{i,j,t}^{ECMS}$ and $\theta_{i,j,t}^{ECMS}$ are the parameters for describing ECMS level and calculating the satisfaction utility function, relating to the electricity consumption feature of $EC_{i,j}$, respectively; $P^0_{i,j,t}$ is the electricity consumption demand of $EC_{i,j}$; and $v_{0,t}$ is the power price.

The constrains are given as follows.

1) Economic constraints

$$\begin{cases} \underline{k}^{ECSM}_{i,j} \le k^{ECSM}_{i,j,t} \le \bar{k}^{ECSM}_{i,j} \\ \underline{k}^{ECSC}_{i,j} \le k^{ECSC}_{i,j,t} \le \bar{k}^{ECSC}_{i,j} \end{cases} \tag{32}$$

$$\underline{P}^{sell}_{i,j,t} \le P^{sell}_{i,j,t} \le P^0_{i,j,t} \tag{33}$$

where $\bar{\alpha}$ and $\underline{\alpha}$ are the maximum and minimum values of the parameter α, respectively.

2) Electricity consumption satisfaction constraints

$$\begin{cases} \underline{\chi}^{ECMS}_{i,j} \le \chi^{ECMS}_{i,j,t} \le \bar{\chi}^{ECMS}_{i,j} \\ \underline{\chi}^{ECCS}_{i,j} \le \chi^{ECCS}_{i,j,t} \le \bar{\chi}^{ECCS}_{i,j} \end{cases} \tag{34}$$

3) Power flow constraints

$$\begin{cases} P^0_{i,j,t} - P^{sell}_{i,j,t} = U_{k,t} \sum_{kk' \ne k, k'=1} U_{k',t}\left(G_{kk'}\cos\theta_{kk',t} + B_{kk'}\sin\theta_{kk',t}\right) \\ Q_{k,t} = U_{k,t} \sum_{kk' \ne k, k'=1} U_{k',t}\left(G_{kk'}\sin\theta_{kk',t} - B_{kk'}\cos\theta_{kk',t}\right) \end{cases} \tag{35}$$

$$\underline{U}_{k,t} \le U_{k,t} \le \bar{U}_{k,t} \tag{36}$$

$$U_{k,t} - U_{k',t} \le 2\left(R_{kk'}P_{kk',t} + X_{kk'}Q_{kk',t}\right) \tag{37}$$

where k is defined as the node of $EC_{i,j}$; k' is the adjacent node of k; U is the node voltage; G and B are the node admittances; and R and X are the node impedances.

2) Model of LA

The objective function of LA_i to coordinate the DR transaction is given by (38) and (39).

$$\max \sum_{t=1} B^{\rho'''}_{i,t} \tag{38}$$

$$B^{\rho'''}_{i,t} = B^{\kappa}_{i,t} + B^{\kappa'}_{i,t} - \sum_{j=1} C^{\lambda}_{i,j,t} - \sum_{j=1} C^{\lambda'}_{i,j,t} \tag{39}$$

where $B^{\kappa}_{i,t}$ is the benefit of LA_i for coordinating DR; $B^{\kappa'}_{i,t}$ is the additional incentive benefit from DNM (refer to Section IV-B); $C^{\lambda}_{i,j,t}$ is the cost of purchasing power from $EC_{i,j}$, whose value equals $B^{\lambda}_{i,j,t}$ (refer to (26)); $C^{\lambda'}_{i,j,t}$ is the additional incentive payment to $EC_{i,j}$, whose value equals $B^{\lambda'}_{i,j,t}$ (refer to (26)); and superscripts κ and κ' denote the abstract models in Section II.

$B^{\kappa}_{i,t}$ can be expressed as:

$$B^{\kappa}_{i,t} = w_{i,t} P^{sell}_{i,t} \tag{40}$$

where $w_{i,t}$ is the power price declared by LA_i to DNM; and $P^{sell}_{i,t}$ is the responsive power volume sold by LA_i to DNM.

$$C^{\lambda}_{i,j,t} = v_{i,j,t} P^{buy}_{i,j,t} \tag{41}$$

where $P^{buy}_{i,j,t}$ is the responsive power volume purchased by LA_i from $EC_{i,j}$.

The constraints are given as follows.

$$P^{sell}_{i,t} = \sum_{j=1} P^{buy}_{i,j,t} \tag{42}$$

$$P^{sell}_{i,j,t} = P^{buy}_{i,j,t} \tag{43}$$

$$P^{sell}_{i,t} = P^{buy}_{i,t} \tag{44}$$

$$\underline{B}^{\rho'''}_{i,t} \le B^{\rho'''}_{i,t} \tag{45}$$

3) Model of DNM

The objective function of DNM in the DR transaction can be expressed as (46).

$$\min \sum_{t=1} \sum_{i=1} \left(-C^{\kappa}_{i,t} - C^{\kappa'}_{i,t}\right) \tag{46}$$

$$C^{\kappa}_{i,t} = \sum_{i=1} w_i P^{buy}_{i,t} \tag{47}$$

$$C^{\kappa'}_{i,t} = B^{\kappa'}_{i,t} \tag{48}$$

The constraints are given as follows.

$$P^{buy}_{i,t} = P^{sell}_{i,t} \tag{49}$$

$$\underline{P}_t \le \sum_{i=1} P^{buy}_{i,t} \le \bar{P}_t \tag{50}$$

B. Satisfaction Cost-sharing Incentive Benefit Based on VCG Theory

Due to the inequality and privacy of information, $EC_{i,j}$ may declare false DR cost function to LA, which can be shown as (51).

$$\tilde{C}^{\varphi}_{i,j,t} = \varphi_{i,j,t}\left(\tilde{x}_{i,j,t}\right) = \tilde{k}^{ECMS}_{i,j,t}\left(1 - \chi^{ECMS}_{i,j,t}\right) + \tilde{k}^{ECCS}_{i,j,t}\left(1 - \chi^{ECCS}_{i,j,t}\right) \tag{51}$$

$EC_{i,j}$ should determine two critical parameters, i. e., $\tilde{k}^{ECMS}_{i,j,t}$ and $\tilde{k}^{ECCS}_{i,j,t}$ (refer to (29)), when declaring the cost function to LA_i. Similarly, LAs must decide the key parameter $\tilde{k}^{ECCS}_{i,t}$ while declaring the cost function as (52).

$$\tilde{C}^{\varphi}_{i,t} = \varphi_{i,t}\left(\tilde{y}_{i,t}\right) = \left(1 + \tilde{k}^{ECCS}_{i,t}\right) \cdot \sum_{j=1} \omega_{i,j}\left[\tilde{k}^{ECMS}_{i,j,t}\left(1 - \chi^{ECMS}_{i,j,t}\right) + \tilde{k}^{ECCS}_{i,j,t}\left(1 - \chi^{ECCS}_{i,j,t}\right)\right] \tag{52}$$

To make ECs and LAs declare their actual cost function for maximizing social welfare, a VCG mechanism-based cost-sharing method is proposed. According to the VCG mechanism, the incentive benefit of one stakeholder is decided by the benefit of other stakeholders participating in the transaction except for his own.

Therefore, the additional incentive benefits of $EC_{i,j}$ and LA_i can be calculated by (53) and (54), respectively.

$$B^{\lambda'}_{i,j,t} = a\left[\sum_{j' \ne j, j'=1} \tilde{C}^{-j,\varphi}_{i,j',t} - \left(\sum_{j=1} \tilde{C}^{\varphi}_{i,j,t} - \tilde{C}^{\varphi}_{i,j,t}\right)\right] \tag{53}$$

$$B^{\kappa'}_{i,t} = b\left[\sum_{i' \ne i, i'=1} \tilde{C}^{-i,\bar{\varphi}}_{i,t} - \left(\sum_{i=1} \tilde{C}^{\bar{\varphi}}_{i,t} - \tilde{C}^{\bar{\varphi}}_{i,t}\right)\right] \tag{54}$$

V. Proofs of Proposed Model

The objective of the mechanism design is to obtain a consensual outcome through the mechanism [36], [37], which generally has some good properties, including ① incentive compatibility; ② individual rationality; ③ cost minimization; and ④ budget balance. Some of these four properties must be satisfied under certain conditions in this paper.

A. Incentive Compatibility

Define $C_{i,t}^{\bar{\varphi}}$ as the actual response cost function declared by LA_i and $\tilde{C}_{i',t}^{\bar{\varphi}}, \forall i' \neq i, i' \in Z^+$ as the response cost function of the other LAs. Define $\boldsymbol{P}^* = \arg\min_{\boldsymbol{P}} \left(\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{\bar{\varphi}} + C_{i,t}^{\bar{\varphi}} \right)$ and $\boldsymbol{P}^\dagger = \arg\min_{\boldsymbol{P}} \sum_{i=1} \tilde{C}_{i,t}^{\bar{\varphi}}$ as the optimal responsive plan of the system when LA_i declares the real and false cost function, respectively. Define $\boldsymbol{P}^{-i} = \arg\min_{\boldsymbol{P}} \sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{-i,\bar{\varphi}}$ as the optimal responsive plan of the system when LA does not participate in transaction.

When declaring the real response cost function, the net profit of LA_i is:

$$N_{i,t}^{\kappa'} = B_{i,t}^{\kappa'}(\boldsymbol{P}^*) - C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) = b\left[\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i}) - \left(\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{\bar{\varphi}}(\boldsymbol{P}^*) + C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) - C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*)\right)\right] - C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) = b\sum_{i' \neq i, i' \in I} \tilde{C}_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i}) - \left(b\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{\bar{\varphi}}(\boldsymbol{P}^*) + C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*)\right) \tag{55}$$

where $\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i})$ means the sum of the response cost of all LAs participating in demand response except LA_i.

When declaring the false response cost function, the net profit of LA_i is:

$$\tilde{N}_{i,t}^{\kappa'} = B_{i,t}^{\kappa'}(\boldsymbol{P}^\dagger) - C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^\dagger) = b\left[\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i}) - \left(\sum_{i=1} \tilde{C}_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^\dagger) - \tilde{C}_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^\dagger)\right)\right] - \tilde{C}_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^\dagger) = b\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i}) - \left(b\sum_{i' \neq i, i' \in I} \tilde{C}_{i',t}^{\bar{\varphi}}(\boldsymbol{P}^\dagger) + \tilde{C}_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^\dagger)\right) \tag{56}$$

where $\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i})$ means the sum of the response cost of all LAs participating in demand response except LA_i.

When LA_i declares the false function $\tilde{C}_{i,t}^{\bar{\varphi}}$, due to the constant planned responsive demand of the system, the response power volume allocated to LA_i will decrease, and other LAs will get more. Meanwhile, $b\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{\bar{\varphi}}(\boldsymbol{P}^{-i})$ is independent of the cost function declared by LA_i, then we have:

$$b\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{\bar{\varphi}}(\boldsymbol{P}^*) + C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) \leq b\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{\bar{\varphi}}(\boldsymbol{P}^\dagger) + C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^\dagger) \tag{57}$$

Therefore, the net profit of LA when declaring the actual response cost is greater than the profit when declaring the false one. Similarly, ECs have the conclusion, i.e., $N_{i,j,t}^{INC} \geq \tilde{N}_{i,j,t}^{INC}$.

In short, in the proposed DR model, the optimal strategies for LAs and ECs are to declare their actual response cost functions. Thus, the proposed DR model satisfies the dominant strategy incentive compatibility.

B. Individual Rationality

According to the previous subsection, LA_i has a robust tendency to declare its actual response cost function, and its net profit can be given by:

$$N_{i,t}^{\kappa'} = B_{i,t}^{\kappa'}(\boldsymbol{P}^*) - C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) = b\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i}) - \left(b\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{\bar{\varphi}}(\boldsymbol{P}^*) + C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*)\right) \tag{58}$$

The last term of (58) can be interpreted as the optimization result after adding a constraint $P_{i,t}^{buy} = P_{i,t}^{sell} \triangleq 0$ to the original model, i.e., the feasible region shrinks; thus, it can be deduced that:

$$\sum_{i' \neq i, i'=1} \tilde{C}_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i}) \geq \sum_{i=1} \tilde{C}_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) \tag{59}$$

Then, (58) can be transformed into:

$$N_{i,t}^{\kappa'} = B_{i,t}^{\kappa'}(\boldsymbol{P}^*) - C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) \geq (1-b)C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) \tag{60}$$

Therefore, when $0 \leq b \leq 1$, LA_i is satisfied with individual rationality. Similarly, for $\mathrm{EC}_{i,j}$, when $0 \leq a \leq 1$, $\mathrm{EC}_{i,j}$ is satisfied with individual rationality.

C. Cost Minimization

Using the proposed VCG-based method, LAs and ECs are willing to participate in the transaction while declaring the actual response functions according to the proof of incentive compatibility and individual rationality. Therefore, the VCG mechanism applied in this paper satisfies the cost minimization of the system.

D. Budget Balance

For LAs, we have:

$$B_{i,t}^{\kappa'} - \sum_{j=1} B_{i,j,t}^{\lambda'} = b\left[\sum_{i' \neq i, i'=1} \tilde{C}_{i,t}^{-i,\bar{\varphi}} - \left(\sum_{i=1} \tilde{C}_{i,t}^{\bar{\varphi}} - \tilde{C}_{i,t}^{\bar{\varphi}}\right)\right] - \sum_{j=1} a\left[\sum_{j' \neq j, j'=1} \tilde{C}_{i,j',t}^{-j,\varphi} - \left(\sum_{j=1} \tilde{C}_{i,j,t}^{\varphi} - \tilde{C}_{i,j,t}^{\varphi}\right)\right] \tag{61}$$

For satisfying individual rationality, LAs and ECs have a robust tendency to declare their actual response functions, which can be shown as (62). Thus, (61) can be simplified as (63).

$$C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) = \sum_{j=1} \omega_{i,j} C_{i,j,t}^{\varphi}(\boldsymbol{P}^*) \tag{62}$$

$$B_{i,t}^{\kappa'} - \sum_{j=1} B_{i,j,t}^{\lambda'} = b\left(\sum_{i' \neq i, i'=1} C_{i',t}^{-i,\bar{\varphi}}(\boldsymbol{P}^{-i}) - \sum_{i' \neq i, i'=1} C_{i',t}^{\bar{\varphi}}(\boldsymbol{P}^*)\right) - \sum_{j=1} a\left(\sum_{j' \neq j, j'=1} C_{i,j',t}^{-j,\varphi}(\boldsymbol{P}_i^{-j}) - \sum_{j' \neq j, j'=1} C_{i,j',t}^{\varphi}(\boldsymbol{P}_i^*)\right) \tag{63}$$

Bringing (63) into (62), we can obtain:

$$B_{i,t}^{\kappa'} - \sum_{j=1} B_{i,j,t}^{\lambda'} \geq bC_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) - \sum_{j=1} aC_{i,j,t}^{\varphi}(\boldsymbol{P}_i^*) \geq (b-a)\left(C_{i,t}^{\bar{\varphi}}(\boldsymbol{P}^*) - \sum_{j=1} C_{i,j,t}^{\varphi}(\boldsymbol{P}_i^*)\right) \tag{64}$$

Thus, when $b - a \geq 0$, a budget balance is established for LAs.

Compared with the traditional DR, DNM is required to pay additional expenses to participants under the proposed method. This expense could lead to the budget imbalance of DNM. However, DNM can allocate the extra expense to the ECs who do not participate in DR or charge the threshold fee of all the ECs participating in the transaction to compensate for the unbalanced budget. Specific discussions are given in Section VI.

VI. Case Studies

This section uses two test systems to verify the proposed method. The proposed method is formulated in MATLAB R2016a, solved by CPLEX solver. The simulation is carried out on a personal computer with a 3.6 GHz Intel Core i5-12600KF processor and 32 GB RAM.

A. IEEE 33-node System

1) Data Description

Figure 3 shows the modified IEEE 33-node system. Four LAs are settled in the area, and all loads are divided into three types [38]. Figure 4 shows the power of the three types of loads in a day. The cost-sharing parameter b is set to be 0.6, and a is set to be 0.4. Parameters for ECMS and ECCS can be found in [27] and [28].

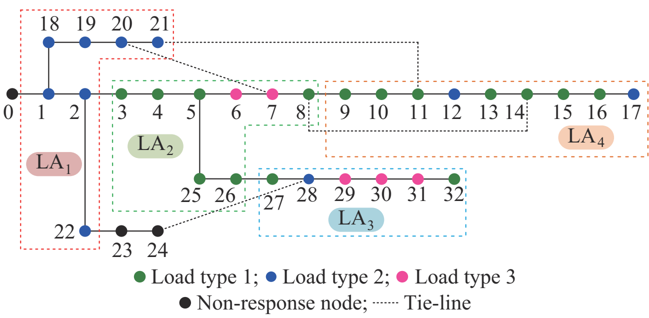

Fig. 3. Modified IEEE 33-node system.

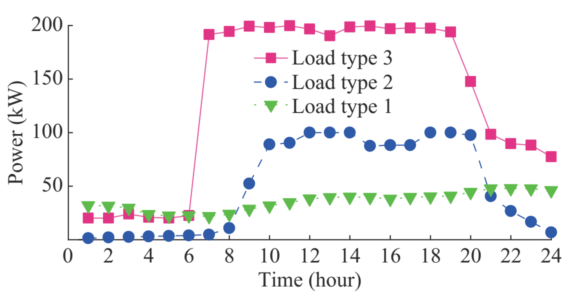

Fig. 4. Power of three types of load in a day.

2) Overall Analysis Under Three Different DR Mechanisms

Figure 5 shows the total response cost and expenditure under three different DR mechanisms, where M1 represents the traditional DR mechanism, M2 represents the cost-sharing mechanism, and M3 represents the proposed VCG-based method in this paper. Generally, the responsive volume of M1 is about 25%-35% lower than those of M2 and M3 during peak periods, while the expenditure under M1 is lower than those under M2 and M3.

Compared with M2, M3 can spend 3%-8% less than M2 with essentially the same response volume. Although there is a slight difference, M3 still gives better results than M2. In actual systems, the percentage of deceptive declarations is usually not very high since too many FRs can alert the market regulator. Overall, the total system expenditure is reduced by a small amount compared with the case where the VCG mechanism is not applied.

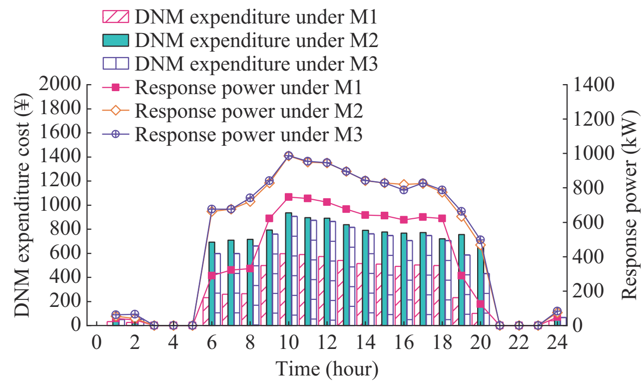

Fig. 5. Total response cost and expenditure under three different DR mechanisms.

3) Economic Analysis of LA

Figure 6 illustrates the response volume and economic composition of LA_3 under three different DR mechanisms.

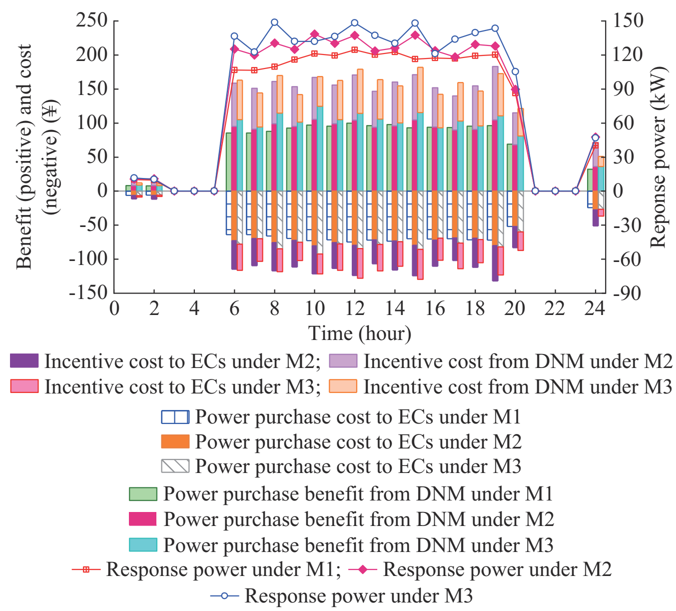

Fig. 6. Response volume and economic composition of LA_3 under three different DR mechanisms.

Unlike the previous subcase, the difference in the effects of M2 and M3 on individuals becomes prominent. In most instances, under M3, the revenue of LA_3 from DNM is partially reduced, but response volume and net profit are increasing. For example, at 19:00, under M2, the total benefit of LA_3 is ¥183.01, the total cost is ¥132.12, and the response volume is 127.86 kW. Under M3, the numbers are ¥172.58, ¥105.01, and 143.49 kW, respectively. The gap between the net profit under the two mechanisms is ¥16.68, approximately 32.8%.

Figure 7 explains the reasons for this phenomenon.

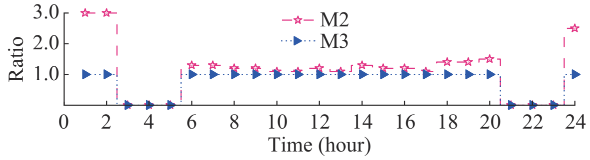

Fig. 7. Ratio of declared value to true value of response cost function under different DR mechanisms for LA_3.

For M2, participants tend to quote strategically, and their declared values are only close to the actual values, even during the peak response periods. However, for M3, the declared value of the participant is consistent with the declared value during all periods; this is precisely what the property of the dominant-strategy incentive capability of the proposed method dictates.

4) Analysis of Benefit

To verify that the proposed VCG-based method in this paper satisfies incentive compatibility, it is assumed that the responders declare critical parameters within a specific percentage range. The result is shown in Fig. 8.

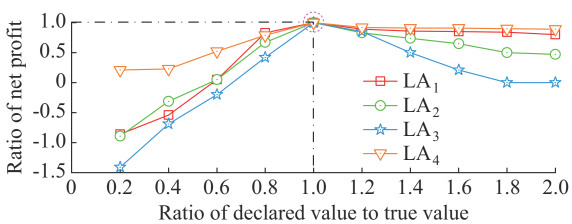

Fig. 8. Ratios of net profit under different coefficients bid by LAs.

For the four LAs, at the only time when the ratio of the declared value to the actual value is 1.0, i.e., $\tilde{k}_{i,t}^{ECS}=k_{i,t}^{ECS}$, the LAs obtain the maximum net profit. When an LA deceptively declares a lower value, the system allocates more response power to the LA, but the payment may not be enough for the response cost. The net profit of LA is reduced or even becomes negative. When an LA falsely declares a higher value, since the fee paid to an LA depends on the impact of this LA on the response cost of other LAs, the impact of this LA on other LAs is reduced, and the payment will also be reduced. For some more specific situations such as LA_3, when it declares too high, it will lose competitiveness, and the net profit will become zero. Another interesting phenomenon is that the more responsive the LA, the greater the penalty for deceptive declaration. LA_3 has a net profit of zero at a declared value of 1.8, but LA_4 still has a net profit of 84% in the same situation. From the perspective of power flow, the nodes managed by LA_3 are located at the end of a branch in the system and are connected to another branch rather than a super trunk. Therefore, power flow has the most significant impact on LA_3. The curve of LA_3 is steeper than other curves. This means that with sufficient response capacity and a lower declaration, LA_3 may not be able to achieve the theoretical optimal response due to the power flow constraint. In short, the transaction results are limited by both the proposed method and the power flow constraint.

B. IEEE 123-node System

In this subsection, we provide a more extensive case study, as shown in Fig. 9, which aims to explore the scalability of the proposed method for a power system with more market players. There are six LAs in the IEEE 123-node system [39].

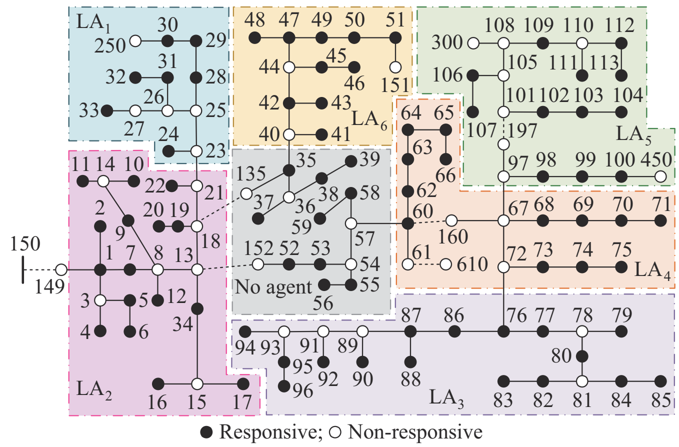

Fig. 9. Illustration of IEEE 123-node system.

1) Impact of Different Deception Ratios on DNM Expenditure

In this case, we change the proportion of deceivers from 0 to 100% to observe changes in DNM expenditure, as shown in Fig. 10.

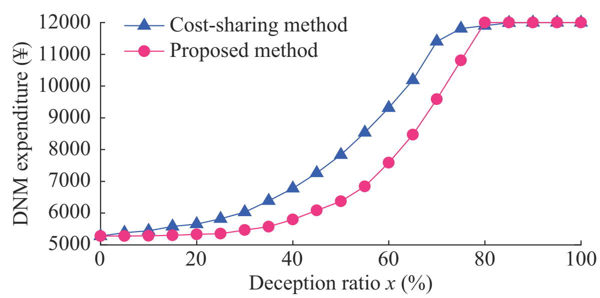

Fig. 10. Impact of different deception ratios on DNM expenditure.

We can divide this figure into three segments.

1) The first segment: $x\in[0,30\%]$. On this segment, we think the proposed method has a good performance. As the number of deceivers increases, the expenditure under the cost-sharing method has sharply increased. When $x=0$, the expenditure of the two methods is both ¥5276.38. However, when $x=30\%$, the expenditure of the cost-sharing method is ¥6031.66, while that of the proposed method is ¥5464.39.

2) The second segment: $x\in[30\%,80\%]$. On this segment, it can be claimed that the proposed method still affects solving the deceptive declaration, but it is beginning to fail. We can see that the slopes of the two curves become similar in this segment from Fig. 10, while on the first segment, the slope of the blue curve tends to be 0. However, it is undeniable that the proposed method is still effective in reducing system costs. For example, when $x=55\%$, the expenditure of the cost-sharing method is ¥8537.88, while the expenditure

of the proposed method is ¥6839.55. The latter represents a 19.9% cost reduction compared with the former.

3) The third segment: $x \in [80\%, 100\%]$. On this segment, the proposed method has wholly failed. The root reason is the vulnerability of the VCG mechanism in the face of complicity. It should be noted that to simulate an actual market regulator, we have set a system payment cap (¥12000); otherwise, the slope of the curve will continue to rise.

In this case, we can conclude that the proposed method and the VCG mechanism have the same weaknesses, namely vulnerability in the face of complicity.

2) Economic Analysis of LA with Different Deception Ratios

In this case, to illustrate more visually how the complicity affects the distributive justice of the proposed method, six subcases are studied, and the results are shown in Fig. 11.

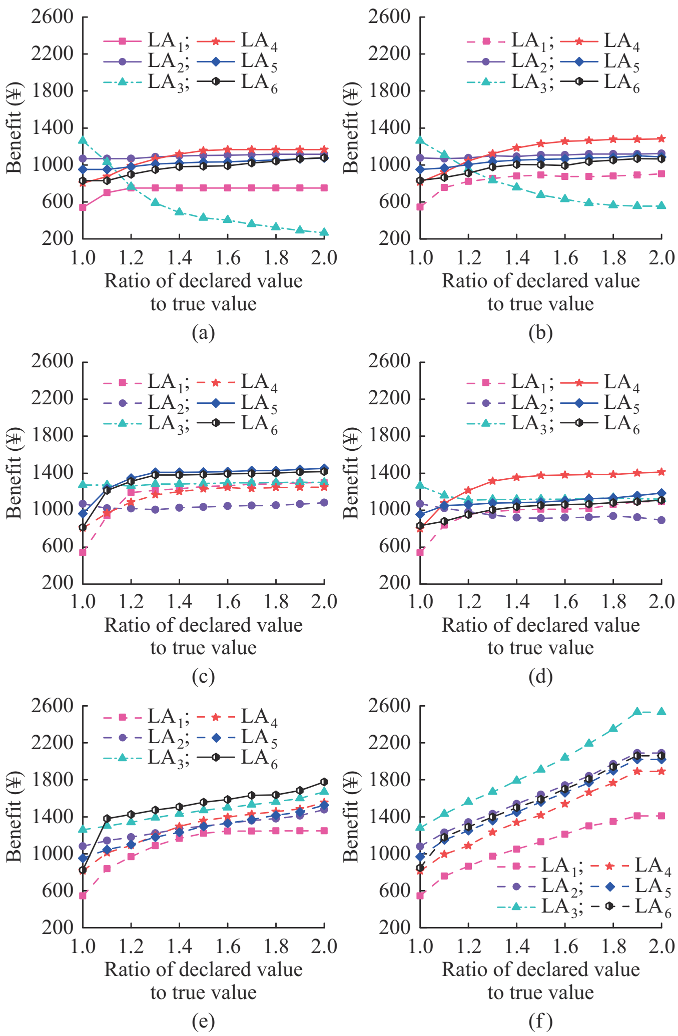

Fig. 11. Economic analysis of LA_3 with different deception ratios. (a) $\{LA_3\}$. (b) $\{LA_1, LA_3\}$. (c) $\{LA_1, LA_2, LA_3\}$. (d) $\{LA_1, LA_2, LA_3, LA_4\}$. (e) $\{LA_1, LA_2, LA_3, LA_4, LA_5\}$. (f) $\{LA_1, LA_2, LA_3, LA_4, LA_5, LA_6\}$.

Defining $\{\cdot\}$ as the set of deceptive declarers, from Fig. 11 (a)-(f), the sets are $\{LA_3\}$, $\{LA_1, LA_3\}$, $\{LA_1, LA_2, LA_3\}$, $\{LA_1, LA_2, LA_3, LA_4\}$, $\{LA_1, LA_2, LA_3, LA_4, LA_5\}$, $\{LA_1, LA_2, LA_3, LA_4, LA_5, LA_6\}$, respectively. In Fig. 11, the dashed lines show the conspirators and the solid lines show the honest ones. When there are fewer declarers at the beginning, falsely declaring can lead to lower profit, as shown in Fig. 11(a) and (b). However, as deceptive declarers become more common, the penalties for deceptive declaration are getting smaller, as shown in Fig. 11(c) and (d), since too many deceptive behaviors occur as unconscious complicity. Ultimately, when complicity takes shape, the inflated price will be even more profitable, as shown in Fig. 11(e) and (f). Another interesting phenomenon is that the number and location of nodes managed by LAs equally affect the transaction results, which is the consequence of power flow influence. Under similar deceleration strategies, as shown in Fig. 11(f), the benefits of LA_1 and LA_4 are significantly less than those of other LAs with similar response capabilities.

3) Budget Balance Analysis

In this case, we have mentioned that DNM could allocate the extra expenditure to the ECs who do not participate in the transaction or charge the threshold fee of all the ECs participating in the transaction to compensate for the unbalanced budget. The total unbalanced budget is ¥25687.20 (18 hours), and two allocation options are proposed below. One solution is to allocate the unbalanced cost to the non-responsive load, as shown in Fig. 12, as the improvement in the quality of operation of the distribution network resulting from DR is available to these loads. Here, the power of loads that do not participate in DR is 61.16 MWh in one day, and the extra charge is 0.8 ¥/kWh.

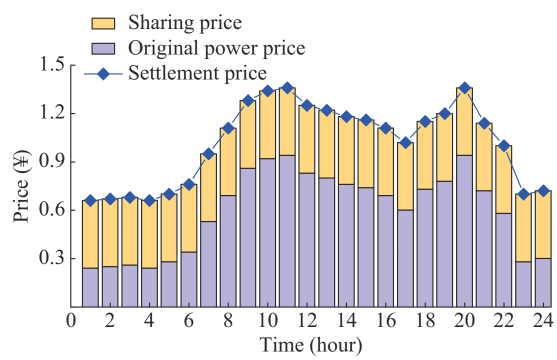

Fig. 12. Settlement price of unbalanced cost apportioned to non-responsive loads in a day.

Another solution is to allocate the unbalanced cost to the responsive load, as shown in Fig. 13. The cost is shared during non-peak periods to guarantee a positive response. The power of loads involved in DR of non-peak periods is 102.75 MWh, then in each non-peak hour, a deduction of 0.25 ¥/kWh is required from the settlement price.

In summary, the two solutions ensure that the DNM budget is balanced and that the ECs are still truthfully declared after deducting some of the costs.

4) Computation Time

Table I shows the computation time of the proposed method for different deception ratios in two test systems. As the proportion of deceivers in the test systems rises, the required computation time rises accordingly, mainly resulting from the increase in the number of iterations.

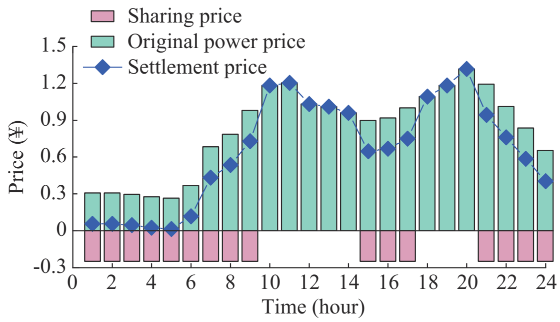

Fig. 13. Settlement price of unbalanced cost apportioned to responsive loads in a day.

TABLE I
COMPUTATION TIME OF PROPOSED METHOD FOR DIFFERENT DECEPTION RATIOS IN TWO TEST SYSTEMS

Test system	Computation time for different deception ratios (s)					
	0	20%	40%	60%	80%	100%
IEEE 33-node	4.76	6.41	7.92	10.86	11.13	10.67
IEEE 123-node	23.87	31.09	37.28	42.14	45.89	45.30

However, when the proportion arrives at a certain point, the computation time will not rise anymore due to the transaction constraints.

VII. CONCLUSION

This paper establishes a price-and-incentive combined DR transaction model based on VCG theory to elicit truthful bids from DR participants, including electric consumers and their aggregators.

The proposed VCG-based method defines the payment to a participant as the incremental costs of the other after removing it, which is proven to fulfill the dominant-strategy incentive compatibility. Case studies based on the IEEE 33-node system and IEEE 123-node system demonstrate some properties and limitations of the proposed method. Firstly, the proposed method could eradicate deceptive behaviors in the cost-sharing transaction framework, and it performs better than the traditional DR model. Secondly, the effectiveness of the proposed method in the face of complicity is studied, which needs to be taken into account in application. Thirdly, two solutions are proposed for the budgetary imbalance created by the proposed method.

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