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Bidding strategy analysis of virtual power plant considering demand response and uncertainty of renewable energy

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Abstract: Due to the gradual exhaustion of petroleum-based energy resources and severe concern for environmental protection, renewable energy (RE) resources and demand response (DR) techniques have been wide deployed in power network. However, the insufficient management as well as technology bottleneck becomes the major obstacle in their further development. Based on the uniform clearing of electricity market, a centralised dispatch model of virtual power plant (VPP) is introduced to improve the competitiveness of distributed energy resources in electricity market. To neutralise the side effect of RE penetration, a bidding strategy optimisation model considering DR and the uncertainty of RE for VPP is proposed and numerical analysis is conducted to prove its applicability. In addition, scenario analysis method is applied to deal with the influence of elastic demand and potential risk, which are associated with utility users' consumption patterns and VPP's bidding preference, respectively. The application of distributed algorithm into multi-players' strategy optimisation problem accelerated the convergence of bidding procedure, which verifies the applicability and effectiveness of the proposed models. Furthermore, numerical case studies demonstrate the distinctive superiority of VPP in the integration and management of RE and DR resources, which in turn contribute to its advantage position in electricity market.

Nomenclature

Subscripts

i	index for market participator
j	index for piece-wise bidding price
k	index for VPP internal distributed generator
t	index for time slot
dg	index for distributed generators
pv	index for photovoltaic plants
wt	index for wind turbines
l	index for renewable energy (RE) scenario

Variables

$P_{\mathrm{wt/pv},t}$	output of wind turbines/photovoltaic plants
$P_{i,\mathrm{t}}$	clearing output of participator i
P_k^{dg}	output of VPP's kth distributed generators

Parameters

Δt	dispatch time interval
T	dispatch period
$\lambda_{\theta,\mathrm{t}}$	market clearing price
θ	marginal generator index
s_i	bidding price set of participator i
ΔP	piece-wise step length for bidding capacity
$\lambda_{i,j}$	stage jth bidding price of participator i
n_i	maximum bidding dimension for participator i
n_s	generated scenarios number
m	number of market participators
$\alpha_{i,j,t}$	binary parameter for clearing results
D_t	utility demand
$P_i^{\max/\min}$	maximum/minimum output of participator i
$P_i^{\mathrm{up/dn}}$	maximum up/down ramp rate of participator i
$\delta_{i,j}$	expected profit for stage jth bidding
$\lambda_{\max}$	maximum bidding price
$\lambda_{\mathrm{vpp}}^{\mathrm{up/dn}}$	maximum up/down price ramp limit of VPP
$\phi_{\mathrm{wt/pv}}$	fixed cost for RE generation
a_i, b_i, c_i	parameters for generator's consumption
$\pi_{\mathrm{up/dn}}$	punish parameters for insufficient/excess power quantity
ρ_t^l	RE output deviation
ψ_t^l	risk cost of RE fluctuation
$L_{\mathrm{s/c},t}$	aggregated constant/controllable load demand of users
$\lambda_{\mathrm{p/n},t}$	demand response positive/negative reaction price
$\pi_{\mathrm{p/n},t}$	demand response positive/negative sensitivity

Functions

$f_i(P)$	fuel-cost of participator i
$\varphi_i(P)$	marginal cost of participator i
$\chi_{i,t}(s_i)$	net revenue of participator i

1 Introduction

With the rapid development of smart grid technology, utility user has transformed into an essential electricity price maker through its participation in demand response (DR) procedure. With the help of smart grid technology, the historical information of the users' consumption preferences could be gathered and analysed precisely [1]. As an effective method to ensure the power balance of electricity market, the application of DR helps neutralise the side-effect of power deviation brought by the intermittent nature of various renewable energy (RE) while maintaining the satisfaction of utility demand in user side [2]. However, existing DR methods aim at improving the management of power network from demand side [3, 4]. By incorporating DR into the framework of smart gird, the independent system operator (ISO) could communicate with utility users about the dynamically updated electricity prices, which formulates the foundation of users' intelligent management towards utility consumption patterns for the sake of cost reduction. For economic dispatch problem, numerous algorithms have been proposed and compared wherein a congestion environment is considered to verify the effectiveness of smart grid [5, 6]. However, due to the penetration of RE in user side [7], power fluctuation and RE curtailment have become the major obstacles in its development and application. Due to its geographically wide distribution and low capacity, distributed RE is difficult to be managed in grid scale. Thus, the concept of virtual power plant (VPP) that integrates multi-regional distributed energy resources (DERs) into a coordinated uniform power utility could improve the competitiveness of RE to participate in all aspects of electricity market [8].

At present, there have been lots of studies on the economic operation and bidding strategy optimisation of VPP. Based on its internal function, VPP could be further divided into technical/ commercial VPP (TVPP/CVPP), the former of which is mainly responsible for the safe operation and technical communication with ISO while the latter focuses on the economic aggregation and bidding strategy optimisation [8–13]. Regarding the market structure of this context, we focus on the market behaviours of VPP and its corresponding performance, which is mainly related to the function of CVPP. In [8, 9], the bidding strategy of VPP in a joint market of energy and spinning reserve service is solved through the combination of price-based unit commitment and genetic algorithm. The results indicated that, through proper allocations of VPP's generation capacity, VPP is able to achieve its maximum profit in the optimised generation profile. In [1], Rahimiyan and Baringo applied robust optimisation to deal with the uncertainty of the integrated wind power in VPP, which positioned itself as a price-taker in the electricity market due to its limited capacity. In [10–13] stochastic optimisation and point estimation method are also applied to analysis the uncertainty of RE. Especially in [12], a bi-level optimisation model is proposed to compromise the contradiction between ISO and VPP. With the growing involvement of DR in smart grid, the DR-based bidding strategies of VPP are analysed in [14–18]. In [18], the application of Nash equilibrium from game theory in electricity bidding procedure enlightens us a brand-new sight in the optimisation operation of VPP. Unlike traditional commercial VPP, the DR-based VPP procured an interactive communication channel between utility users and power providers, which contributed to a reliable equilibrium between supply and demand sides [19].

Given previous progress, this paper's contributions are fourfold:

(a) A modified market-based electricity clearing procedure is proposed in accordance with interactive smart grid structure, which guarantees the dynamic equilibrium between supply and demand sides.
(b) A piece-wise comprehensive VPP cost model is built based on the coordinated economic dispatch of VPP's internal DERs, where the risk punishment related to the fluctuation of RE is taken into account through the application of scenario analysis.
(c) A bidding strategy optimisation model, which is applicable for both the VPP and conventional generators, is proposed. In addition, a distributed algorithm is applied to solve the proposed model, which accelerates the computation speed of the bidding procedure.
(d) The convergence of the proposed electricity exchange mechanism is analysed based on the assumption that all participators are rational and benefit seeking. Also, the effectiveness of the proposed market procedure is proven to be a win–win situation, which not only reduces users' expense but also increases utility company's profit.

The content of this paper is constructed as follows. Section 2 establishes the basic principle and clearing procedure of the interactive electricity market. In Section 3, the piece-wise comprehensive VPP cost model will be presented. In addition, the bidding strategy optimisation methods of all participators will be presented and the uncertainties of the RE resources will be taken into consideration in this section. In Section 4, the computational flow and mathematical methods which were used to solve the proposed model are introduced. Case study and results are presented in Section 5. Finally, the conclusions are drawn in Section 6.

2 Structure of electricity market

Since the revolution of electricity power system in 1992, a lot of regional electricity markets have been built across United States [13]. According to Federal Energy Regulatory Commission (FERC), the foundation of regional electricity market improves the free competition in the traditional monopolised electricity industry. However, in order to improve the reliability of electricity market, necessary regulations and proper procedures need to be established.

Under the framework of smart grid technology, the real-time information channel beneath all aspects of electric power grid could be built with the deployment of advanced metering infrastructure (AMI) in user-side [20]. Thus, the traditional electricity market could be modified into a dynamic interactive electricity market, which enables the exchange of vital information between market participants. Traditionally, pay as bid (PAB) and market uniform clearing are the two most frequently adopted clearing procedures. In accordance with China's future electricity reformation, we assume that the day-ahead market operates on a unified market clearing price (MCP) and has a dispatch period of T and a dispatch interval of Δt. The other regulations for bidders' participation in the market are defined as follows [21, 22]:

(a) Before the end of Day N's electricity market, all participators propose its bidding information for Day $N+1$'s electricity market, which includes the discrete piece-wise offers of the output and the charges for the corresponding generation.
(b) All utility users submit utility demand to ISO along with the willing DR information.
(c) After ISO collects all game participators' bidding information, ISO will execute market-clearing procedure and publish the MCP $\lambda_{\theta,t}$ along with the accepted bids of all participators.
(d) After the announcement of the market clearing results, all participators are allowed to resubmit their updated bidding strategies based on the limited information provided by ISO.
(e) After the resubmission of all participators, if all participators have no intention to deviate from the latest clearing results, the bidding procedure of day-ahead market will be settled. Otherwise, ISO will conduct steps (c)–(e) until the terminal criterion for iteration is achieved or no deviation is submitted. Despite of the market clearing responsibility, the electricity operation safety issues including power flow limit are also guaranteed by ISO, which has incorporated the function of monitoring the operation of power network. Once a safety violation is detected, ISO will react to eliminate the violation and ensure the safe operation of the electricity system.

We assume that VPP is regarded as a uniform independent participator and need to be responsible for its proposed bidding strategy which should have taken all of its generators' economic parameters into consideration.

In order to reduce the computational burden of ISO, we assume that the piece-wise step of generation bidding ΔP is determined in advance by ISO. As a consequence, the submitted bidding information of player i could be simplified from price and capacity pairs into the set of prices $s_i = \{\lambda_{i,1} \ldots \lambda_{i,j} \ldots \lambda_{i,n_i}\}$. Also, the number of participators in day-ahead market is presumed m without loss of generality. Thus, ISO will receive $\sum_{i=1}^{m} n_i$ piece-wise bidding prices in total and the clearing procedure of ISO in every interval of the dispatch cycle is similar, which could be expressed as the following social cost minimisation problem (1).

For every time slot $t \in T$

$$\min_{\lambda_{\theta,t}} \sum_{i=1}^{m} \sum_{j=1}^{n_i} \alpha_{i,j,t} \lambda_{i,j} \Delta P \tag{1a}$$

S.t.

$$\alpha_{i,j,t} = \begin{cases} 1 & \lambda_{i,j} \le \lambda_{\theta,t} \\ 0 & \lambda_{i,j} > \lambda_{\theta,t} \end{cases} \tag{1b}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n_i}\alpha_{i,j,t}\Delta P \geq D_t \tag{1c}$$

$$\left(\sum_{i=1}^{m}\sum_{j=1}^{n_i}\alpha_{i,j,t}-1\right)\Delta P < D_t \tag{1d}$$

where $\lambda_{\theta,t}$ is the MCP determined by ISO for time slot t and $\alpha_{i,j,t}$ is the binary parameter, which is used to represent the acceptance or reject status of market participator i's number jth bidding strategy in time slot t. Regarding the framework of electricity market, the submitted bidding offers can be accepted only if they are less than MCP, i.e. $\alpha_{i,j,t}=1$, otherwise those offers will be rejected, i.e. $\alpha_{i,j,t}=0$, as illustrated in (1b).

To solve problem (1), the bubble sort algorithm is applied by ISO to reschedule all participators' bidding strategy from the lowest to the highest [23]. Based on the utility demand information, ISO will not accept each participator's submitted bidding strategy in the rescheduled sequence until (1c) and (1d) are both satisfied, which determines the marginal participator θ and the corresponding MCP $\lambda_{\theta,t}$. The settled commitment of each participator could be calculated as (1e) where the output of marginal participator, i.e. $i=\theta$, is determined on behalf of market power balance

$$P_{i,t}=\begin{cases}\sum_{j=1}^{n_i}\alpha_{i,j,t}\Delta P & \forall i=1,\dots,m,\quad i\neq\theta\\ D_t-\sum_{\substack{i=1\\ i\neq\theta}}^{m}P_{i,t} & i=\theta\end{cases} \tag{1e}$$

3 Bidding strategy optimisation analysis

In this section, the monetary cost of market participators will be analysed and the piece-wise comprehensive cost model of VPP will be presented in order to integrate different sorts of DERs. In addition, a distributed bidding strategy optimisation model of all market participators will be proposed based on the limited information exchange between the ISO and the participator.

3.1 Conventional participator's bidding strategy

According to the present compositions of power grid, the majority of the power demand is supplied by traditional fuel-based generators, which are also assumed to be vital parts of this day-ahead market bidding game [24, 25]. In accordance with the market regulations, the bidding strategy space set of the conventional participator could be defined as a combination of basic fuel cost with the expected profit, which satisfies the following constraints.

For every time slot $t\in T$

$$f_i(P_{i,t})=a_iP_{i,t}^2+b_iP_{i,t}+c_i \tag{2a}$$

$$\varphi_{i,j}(j\Delta P)=f_i(j\Delta P)-f_i((j-1)\Delta P) \tag{2b}$$

$$\lambda_{i,j}=\varphi_{i,j}(j\Delta P)+\delta_{i,j} \tag{2c}$$

$$n_i\Delta P\leq P_i^{\max} \tag{2d}$$

$$\delta_{i,j}\geq 0 \tag{2e}$$

$$\lambda_{i,j}\leq\lambda_{\max} \tag{2f}$$

$$\lambda_{i,j-1}\leq\lambda_{i,j}\leq\lambda_{i,j+1} \tag{2g}$$

$$P_i^{\min}\leq P_{i,t}\leq P_i^{\max} \tag{2h}$$

$$P_i^{\text{dn}}\leq P_{i,t}-P_{i,t-1}\leq P_i^{\text{up}} \tag{2i}$$

where constraints (2a)–(2c) are used to generate the piece-wise bidding strategy set of participator i and constraints (2d)–(2i) are the constraints related with market regulations. Constraint (2d) determines the dimension of participator i's strategy set and constraint (2g) ensures the non-decreasing characteristic of the bidding set. Above all, the bidding strategy set s_i of participator i could be formulated while the strategy space of participator i that satisfies all the constraints is defined as $S_i, \forall s_i\subseteq S_i$.

3.2 VPP's cost and bidding strategy

In order to achieve its maximum net profit, a centralised dispatch strategy of VPP is preferred. However, along with the benefits of centralised dispatch is the unavoidable obstacle that VPP needs to compromise the fluctuation of RE once the commitment of VPP is settled. Thus, it is essential to incorporate the uncertainty of RE into the comprehensive cost model of VPP.

3.2.1 VPP comprehensive cost model: In order to analyse the comprehensive cost of VPP, proper forecast method of RE should be conducted to improve the accuracy. As lots of scientific researches have focused on this aspect and numerous mathematical methods have been applied to improve it, the forecast method of RE is falling out of scope of this paper. Through proper forecast method, we can get the expected output sets of wind turbines (WTs) and photovoltaic (PV) denoted as $\{P_{\text{wt},t}\}$ and $\{P_{\text{pv},t}\}$, respectively [14]. Also, according to [10, 11], the monetary cost of RE generation is considered as a linear function of its output. Thus the comprehensive piece-wise cost model of VPP could be defined as a cost minimisation problem (3).

$$\min_{P_k^{\text{dg}}} f_{\text{vpp}}(j\Delta P),\quad \forall j=1,\dots,n_{\text{vpp}} \tag{3a}$$

S.t.

$$f_{\text{vpp}}(j\Delta P)=\phi_{\text{wt}}\overline{P}_{\text{wt}}+\phi_{\text{pv}}\overline{P}_{\text{pv}}+\sum_{k=1}^{n_{\text{dg}}}f_k^{\text{dg}}(P_k^{\text{dg}}) \tag{3b}$$

$$f_k^{\text{dg}}(P_k^{\text{dg}})=a_k^{\text{dg}}(P_k^{\text{dg}})^2+b_k^{\text{dg}}P_k^{\text{dg}}+c_k^{\text{dg}} \tag{3c}$$

$$\overline{P}_{\text{wt}}=\frac{1}{T}\sum_{t=1}^{T}P_{\text{wt},t} \tag{3d}$$

$$\overline{P}_{\text{pv}}=\frac{1}{T}\sum_{t=1}^{T}P_{\text{pv},t} \tag{3e}$$

$$\overline{P}_{\text{wt}}+\overline{P}_{\text{pv}}+\sum_{k=1}^{n_{\text{dg}}}P_k^{\text{dg}}=\text{j}\Delta P \tag{3f}$$

$$n_{\text{vpp}}\Delta P\leq\overline{P}_{\text{wt}}+\overline{P}_{\text{pv}}+\sum_{k=1}^{n_{\text{dg}}}P_k^{\text{dg,max}} \tag{3g}$$

$$P_k^{\text{dg,min}}\leq P_k^{\text{dg}}\leq P_k^{\text{dg,max}},\quad \forall k=1,\dots,n_{\text{dg}} \tag{3h}$$

Due to the fact that all participators are allowed to submit a unique bidding strategy during the entire dispatch period. Thus, the comprehensive cost model of VPP needs to decouple time correlation coefficients of RE, where the use of constraints (3d) and (3e) aims at reducing the temporality of RE output. Meanwhile constraint (3f) is associated with power balance requirement and (3g) determines the maximum value of VPP's bidding set dimension.

3.2.2 VPP piece-wise bidding strategy: After the solution of VPP's internal unit commitment problem, the comprehensive cost set of VPP could be formulated. Based on the information of VPP's comprehensive cost, VPP is able to determine its piece-wise bidding strategy denoted as $s_{\mathrm{vpp}}=\left\{\lambda_{\mathrm{vpp},1}\cdots\lambda_{\mathrm{vpp},j}\cdots\lambda_{\mathrm{vpp},n_{\mathrm{vpp}}}\right\}$, where $\lambda_{\mathrm{vpp},j}$ represents the proposed price of VPP for the supplement of stage jth power quantity and the correlation between it and the comprehensive cost satisfies the following constraints:

$$\lambda_{\mathrm{vpp},j}=f_{\mathrm{vpp}}(j\Delta P)-f_{\mathrm{vpp}}((j-1)\Delta P)+\delta_{\mathrm{vpp},j} \tag{3i}$$

$$\lambda_{\mathrm{vpp},j-1}\le\lambda_{\mathrm{vpp},j}\le\lambda_{\mathrm{vpp},j+1} \tag{3j}$$

$$\lambda_{\mathrm{vpp}}^{\mathrm{dn}}\le\lambda_{\mathrm{vpp},j}-\lambda_{\mathrm{vpp},j-1}\le\lambda_{\mathrm{vpp}}^{\mathrm{up}} \tag{3k}$$

$$\lambda_{\mathrm{vpp},j}\le\lambda_{\max} \tag{3l}$$

$$0\le\delta_{\mathrm{vpp},j} \tag{3m}$$

Constraints (3j)–(3k) ensure the non-decreasing characteristic of VPP's bidding information as well as the upper-limit of the bidding price. Through the combination of the comprehensive cost model and the piece-wise bidding strategy, the strategy space of VPP could be defined as S_{vpp} that for every $s_{\mathrm{vpp}}\subseteq S_{\mathrm{vpp}}$ the constraints of problem (3) could be satisfied on all conditions.

3.3 Conventional participators' bidding strategy optimisation

According to the above analysis, all participators of the day-ahead market could select bidding strategy s_i from its available strategy space S_i. Based on the electricity clearing procedure introduced in Section 2, all submitted bidding information are private while the clearing results λ_θ and P_i are public. Thus, the optimisation problem of individual bidding strategy could be solved through the application of distributed algorithm [26] and the privacy of each participator could be protected [27], which enables the participator update its bidding strategy according to the limited public information for the sake of its maximum revenue. The individual strategy optimisation problem of participator i in each clearing stage could be expressed as follows:

$$\max_{s_i,s'_i\subseteq S_i}\sum_{t=1}^{T}\left[\chi_{i,t}(s_1\cdots s'_i\cdots s_m)-\chi_{i,t}(s_1\cdots s_i\cdots s_m)\right] \tag{4a}$$

S.t.

$$\chi_{i,t}(s_1\cdots s_i\cdots s_m)=\lambda_{\theta,t}P_{i,t}-f_i(P_{i,t}) \tag{4b}$$

$$\chi_{i,t}(s_1\cdots s'_i\cdots s_m)=\lambda_{\theta,t}P'_{i,t}-f_i(P'_{i,t}) \tag{4c}$$

$$\alpha'_{i,j,t}=\begin{cases}1 & \lambda_{i,j}\le\lambda'_{\theta,t}\\ 0 & \lambda_{i,j}>\lambda'_{\theta,t}\end{cases} \tag{4d}$$

$$P'_{i,t}=\sum_{j=1}^{n_i}\alpha'_{i,j,t}\Delta P \tag{4e}$$

where (4a) aims at the maximisation of participator's revenue increase and (4b)–(4e) represent the optimisation of strategy s_i with limited clearing result information. The convergence and mathematical solution method of this procedure will be discussed in Section 4.

3.4 VPP bidding strategy optimisation

In order to neutralise the side effect of the RE, power adjustment of VPP's output should be conducted to improve the stability of VPP's output. Due to the energy resources' property constraints, the controllable energy resource in VPP is confined to its internal distributed generators, which could adjust their realistic output to meet the requirement of power balance. As a consequence, monetary compensation will be paid to the generators whose outputs have been altered, which directly leads to the decrease of VPP's net revenue. To consider the uncertainty effects, the scenario-based risk analysis of VPP is introduced. Different from Monte Carlo simulation (MCS), the application of scenario analysis method could avoid complex computation burden brought by the deployment of MSC method. In addition, scenario-based uncertainty analysis could account for the temporal correlation of PV/WT, which contributes to a more reliable and comprehensive assessment of VPP's potential risk cost [28].

Based on the historical output data of WT and PV, the empirical distribution function of RE output could be achieved, which is the foundation to generate typical scenario of RE output. Through the application of scenario reduction methods, the typical output of WT and PV could be categorised into n_s typical scenarios defined as $\left\{P_{\mathrm{wt},t}^{l}\right\}$ and $\left\{P_{\mathrm{pv},t}^{l}\right\}$ where $l=1,\ldots,n_s$. On account of the generated typical scenarios, the influence of RE uncertainty could be analysed as follows:

$$\max_{s_i,s'_i\subseteq S_i}\sum_{t=1}^{T}\left[\chi_{i,t}(s_1\cdots s'_i\cdots s_m)-\chi_{i,t}(s_1\cdots s_i\cdots s_m)\right]-\psi \tag{5a}$$

S.t.

$$\text{constraints (4b)}-\text{(4e)} \tag{5b}$$

$$\rho_t^l=P_{\mathrm{wt},t}^l+P_{\mathrm{pv},t}^l-P_{\mathrm{wt},t}-P_{\mathrm{pv},t} \tag{5c}$$

$$\psi_t^l=\begin{cases}-\pi_{\mathrm{up}}\rho_t^l\lambda_\theta & \rho_t^l<0\\ 0 & \rho_t^l=0\\ \pi_{\mathrm{dn}}\rho_t^l\lambda_\theta & \rho_t^l>0\end{cases} \tag{5d}$$

$$1\le\pi_{\mathrm{up}}\le\pi_{\mathrm{up}}^{\max} \tag{5e}$$

$$\pi_{\mathrm{dn}}^{\min}\le\pi_{\mathrm{dn}}\le1 \tag{5f}$$

$$\psi=\frac{1}{T}\frac{1}{n_s}\sum_{t=1}^{T}\sum_{l=1}^{n_s}\psi_t^l \tag{5g}$$

where (5a) incorporates the average risk cost of VPP's RE fluctuation into its expected revenue. The constraints (5b)–(5f) are used to calculate the risk cost of VPP in scenario l while (5g) calculates the average risk value in the end [29]. The different calculation formulas in (5d) represent the situation of power insufficient, power equality and power excess separately. The parameters π_{up} and π_{dn} in (5d) are determined by VPP in advance as surplus monetary punishments for power rescheduling.

3.5 Demand side management

With the help of AMI in user side, the variation of utility demand could be communicated with ISO in time, which enables the involvement of DR during market clearing procedure. Let D_t denote the expected load aggregation of customers in time slot t, which could be divided into constant load demand $L_{s,t}$ and flexible load requirement $L_{c,t}$ according to users' consumption patterns. Also, consumers will determine the DR trigger price in advance, which contains both positive and negative reaction prices. Thus the DR management could be formulated as (6) as follows:

$$D_t=\begin{cases}L_{s,t}+L_{c,t}+\pi_p(\lambda_{p.t}-\lambda_{\theta,t}) & \lambda_{\theta,t}\le\lambda_{p,t}\\ L_{s,t}+L_{c,t}-\pi_n(\lambda_{\theta,t}-\lambda_{n,t}) & \lambda_{\theta,t}\ge\lambda_{n,t}\\ L_{s,t}+L_{c,t} & \text{else}\end{cases} \tag{6a}$$

where DR will be launched when the MCP $\lambda_{\theta,t}$ exceeds the predetermined negative reaction price $\lambda_{\mathrm{n},t}$ or decreases below the positive reaction price $\lambda_{\mathrm{p},t}$

Above all, through the combination of problem (2) and (3), the minimum piece-wise cost model $f_i(P_i)$ of all market participators could be built, which determines the scope of participators' bidding

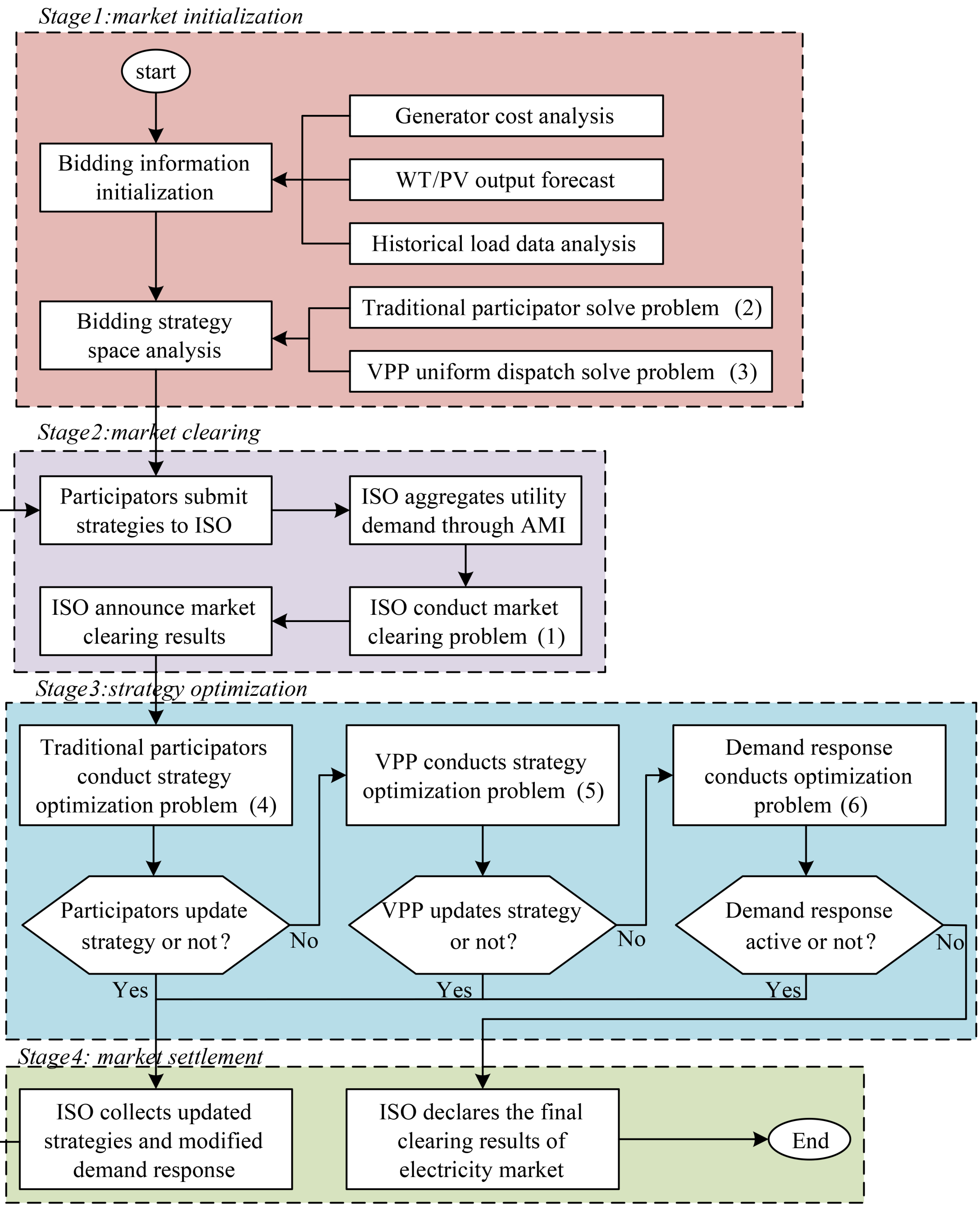

Fig. 1 *Comprehensive market clearing procedure*

strategy space S_i. At the same time, the distributed strategy optimisation model in (4) and (5) could figure out the best bidding strategy s_i from participator's strategy space, which may bring the maximum revenue for the participator in day-ahead market. In addition, the involvement of DR management (6) in utility user side could enhance the stability of power balance in whole electricity system.

4 Mathematical solution

Based on the illustrated market clearing procedure and the mathematical calculation model in the above sections, the comprehensive computation process could be described as Fig. 1.

In order to solve the proposed optimisation procedure, a distributed algorithm is introduced in each participator's strategy optimisation. Due to the limited information provided to all participators, the updated bidding strategy of each participator may result in equilibrium deviation, which is under the influence of other participators' chosen strategies. As a consequence of participator's pursuit on profit maximisation, this interactive market structure's equilibrium convergence deserves further discussion.

Suppose the convergence clearing results of day-ahead market in time slot t are denoted as $\hat{\lambda}_{\theta,t}$ and $\left\{\hat{P}_{1,t}\cdots\hat{P}_{i,t}\cdots\hat{P}_{m,t}\right\}$. For each participator, the final settled bidding information is defined as $\hat{s}_i = \left\{\hat{\lambda}_{i,1}\cdots\hat{\lambda}_{i,n_i}\right\}$, which keeps private until the termination of bidding procedure.

We assume that $s'_i = \left\{\lambda'_{i,1}\cdots\lambda'_{i,n_i}\right\}$ is a deviated bidding strategy of participator i for the sake of individual profit maximisation. It's obvious that all participators should be rational and no strategy would be accepted if the corresponding profit were expected to decrease. Thus, the possible consequence of the deviated strategy could be analysed as follows.

For $j \le n_i$:

(1) $\hat{\lambda}_{i,j} < \lambda_{\theta,t}$ *and* $\lambda'_{i,j} < \lambda_{\theta,t}$: Since this modification of bidding strategy only changes the market clearing sequence of submitted bidding slot, thus it has no influence neither on the MCP nor on the accepted bids of each participator.

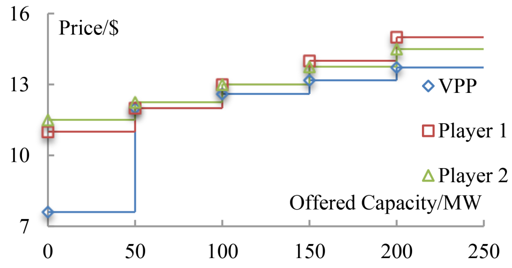

Fig. 2 *Cost curve of each player*

(2) $\hat{\lambda}_{i,j} < \lambda_{\theta,t}$ *and* $\lambda'_{i,j} \geq \lambda_{\theta,t}$: As a rational participator, no such action would be conducted because it could lead to the degradation of participator's original bidding slots' market clearing sequence, which would result in the decrease of its individual output and profit as well.

(3) $\hat{\lambda}_{i,j} > \lambda_{\theta,t}$ *and* $\lambda'_{i,j} > \lambda_{\theta,t}$: Similar with case (1), the update of such bidding strategy could not change the status of the rejected bidding slots and the output of the participator remains unchanged.

(4) $\hat{\lambda}_{i,j} > \lambda_{\theta,t}$ *and* $\lambda'_{i,j} < \lambda_{\theta,t}$: The decrease of submitted bidding prices beyond MCP is the most commonly accepted strategy for participator to increase its basic share of the clearing output, i.e. $P'_{i,t} > \hat{P}_{i,t}$. However, this strategy would result in the decrease of MCP, i.e. $\lambda'_{\theta,t} < \hat{\lambda}_{\theta,t}$ due to the increase of more accepted price slots beyond the original MCP. As a consequence, this strategy breaks the original equilibrium through the change of MCP and marginal generator, which results in the decrease of other participators' profit. Thus, the bidding strategies of other participators will be updated in a similar way in order to increase its individual share of clearing output. It's obvious to notice that the curriculum of such disordered irrational updated strategy would finally result in the decrease of MCP and the final clearing output would be determined by each participator's minimum generation cost set which contradicts with the original intention of electricity market establishment.

(5) $\hat{\lambda}_{i,j} > \lambda_{\theta,t}$ *and* $\lambda'_{i,j} = \lambda_{\theta,t}$: Participator who obtains such strategy is obviously focusing on achieving the advantage of marginal player. Suppose the original marginal player intends to increase its marginal bidding price in seeking for more profit, the player who obtains this strategy could successfully transform into the new marginal player with more share of the clearing output. Even if the original marginal player remains its bidding strategy, the participator could still get half of the marginal generation shares as a reward which could increase its individual output and profit as well. However, as a reaction, the original marginal player's output would suffer through reduction, which may in turn lead to the decrease of marginal player's bidding prices in order to regain its scheduled output.

5 Case study

The case study depends on the modified IEEE-30 bus system obtained from [30] where the key parameters for each unit as well as their belongings and locations are presented in Table 1. According to [31], we could use historical output data of RE to stand for the simulated scenarios. Thus, 100 typical historical output scenarios of PV and WT are adopted in risk assessment, which is provided by a RE generation corporation in East China. Based on the principle of distributed algorithm, the decision variables of each participator are different from each other, which results in the different computation burden of each market participator. In order to solve the aforementioned problem, matlab2014 with matpower package is applied to support our simulation, which is conducted by a 3.6 GHz Intel-Core i7 processor with 8 GB RAM. Since the optimality gap of each market participator's strategy is set to 0.0001, thus the execution time of the model is 150 s with 300 iterations in total. The detailed background of this model along with its simulation result is presented as follows.

To improve the competitiveness of the electricity market, two conventional participators and one VPP are considered during the following analysis, i.e. $m = 3$. Also, the maximum capacity and bidding price of each participator is presumed 250 MW and \$22 separately. Meanwhile, the piece-wise step length of bidding strategy ΔP is set as 50 MW for the sake of computation reduction. According to players' generation properties, the cost curve of each player could be expressed piece-wisely in Fig. 2, which also serves as the lower limit of each player's strategy space at the same time.

In Fig. 2, VPP manages to maintain a lower cost by using RE in advance. However, the cost curve of VPP increases significantly when distributed generators are called on to produce. While the cost of the other conventional players remains stable.

5.1 Influence of consumers' price sensitivity

In order to evaluate the influence of price sensitivity, six different types of consumers are considered during the analysis. The different types of utility users are concluded based on the consumption patterns in [30]. The DR reaction prices in all cases are defined as $\lambda_{n,t} = 15$ \$ and $\lambda_{p,t} = 13.5$ \$, respectively, while the punish parameters of VPP for power unbalance are set to be $\pi_{up} = 0.5$ \$/MW and $\pi_{dn} = 1.5$ \$/MW uniformly.

From Table 2, we could figure out that the utility demand in case 1 is all constant demand and no flexible demand is adopted in this case. However, the utility users in other cases prefer to modify their utility demand according to the updated electricity prices, which contributes not only to utility cost reduction but also to the benefit of social welfare. Based on the assumed cases, the clearing results of the market and the equilibrium strategies of all players are presented as follows.

From Fig. 3, an obvious power shift phenomenon is presented, which verifies the effectiveness of DR. As more flexible utility demand shift from peak hours into valley periods, the PAR of MCP will demonstrate a downswing tendency in response while the MCPs in valley periods are likely to increase as a reaction of output uplift. In addition, from the statistical results in Table 3, the total cleared output of the market is decreased as well as the average MCP due to the involvement of DR, which prohibits the unnecessary flexible demand in peak hours.

Besides the influence of price sensitivity on market clearing results, it also has a tremendous effect towards market participators' bidding strategy as presented in Fig. 4. Due to the low-cost nature of RE, VPP guarantees the commitment priority of

Table 1 Data for each unit in the system

Player		Bus	P_{max}	P_{min}	Ramp rate	Consumption parameters		
						a, \$/MW^2	b, \$/MW	c, \$
1		1	125	25	30	0.02	10	0
		13	125	25	30	0.02	10	0
2		5	125	25	30	0.015	10.75	0
		8	125	25	30	0.015	10.75	0
VPP	WT	2	40	0	5	0	8	0
	PV	2	10	0	2	0	6	0
	DG	6	2*50	0	5	0.025	11.5	0
			2*50	0	5	0.02	12	0

Table 2 Consumers' price sensitivity under different cases

Case number	Positive parameter, MW/$	Negative parameter, MW/$
1	0	0
2	10	10
3	20	20
4	30	30
5	40	40
6	50	50

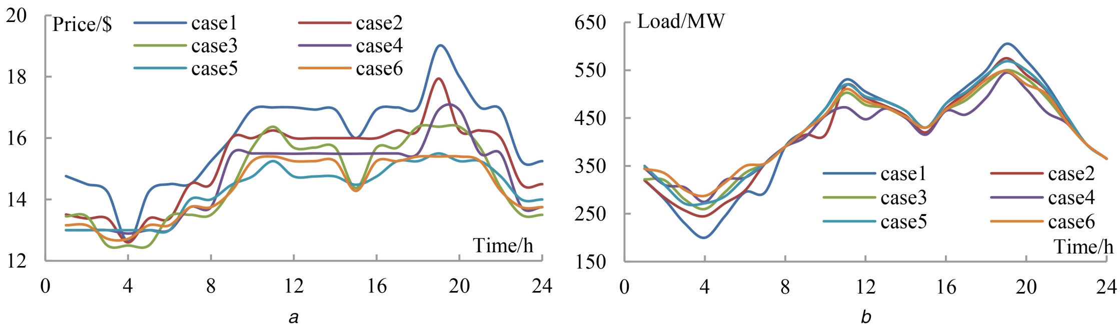

Fig. 3 *Clearing results of day-ahead market*
(a) MCP under different price sensitivity, ***(b)*** Total clearing output under different price sensitivity

Table 3 Key features of clearing results under different cases

Case number	Output		Price	
	PAR	Average, MW	PAR	Average, $
1	3.0	417.5	1.50	16.0
2	2.3	416.6	1.42	15.2
3	2.1	415.7	1.31	14.6
4	1.9	413.5	1.28	14.7
5	2.1	419.8	1.19	14.3
6	2.0	418.8	1.21	14.4

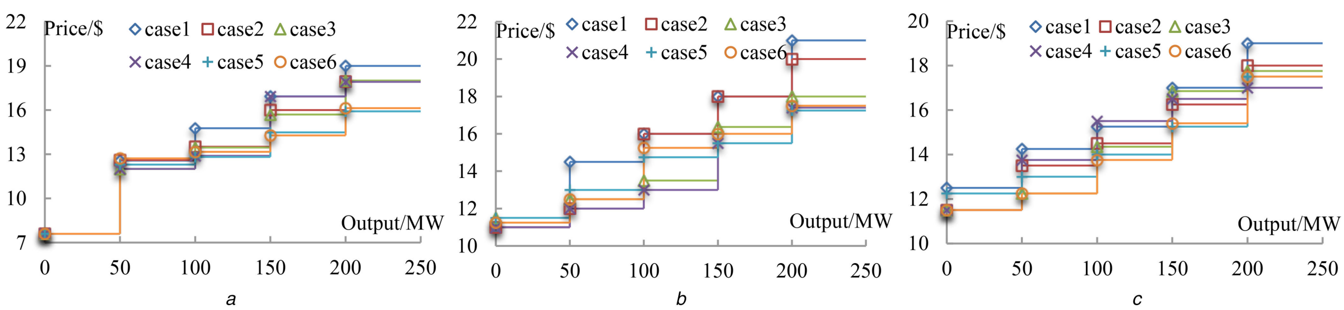

Fig. 4 *Equilibrium bidding strategies of players under different price sensitivity*
(a) VPP's equilibrium bidding strategy, ***(b)*** Player 1's equilibrium bidding strategy, ***(c)*** Player 2's equilibrium bidding strategy

RE by submitting same prices in all cases as illustrated in the first bidding curve of Fig. 4*a*, which in turn ensures the cost advantage of VPP as well. Judged from the cost function provided in Table 1, the generation cost of player 1 is likely to increase much more faster than player 2, which leads to the difference between the two players' bidding strategy in high generation capacity as illustrated in Figs. 4*b* and *c*. Compared with case 1 where no DR is adopted, the bidding strategies of market players become more conservative due to the increase of price sensitivity in utility users, especially in cases 5 and 6 where the submitted prices of all players are almost concentrated in a limited range of DR reaction prices in order to avoid DR overreaction. However, due to the high price sensitivity of consumers in both negative and positive directions, more load requirement is committed in price valley periods, which results in the increase of average load demand and lower PAR as presented in Table 3. Due to players' conservative strategy towards high price sensitivity, the volatility of MCP in cases 5 and 6 becomes smoother compared with other cases as indicated in Fig. 3, which in turn also results in the lower average MCP and smoother load curve. The detailed results of all market players during the entire bidding period are summarised in Table 4.

From Table 4, due to the gradual increase of consumers' price sensitivity, the net profit of each participator suffers an obvious downswing. As the total output of each player is expected to keep stable, the MCP is also confined to the rational level, which prohibits the market from extreme high or low price. Thus, the surplus revenue for players in market peak hours is strictly constrained while the net revenue in valley periods is expected to increase. From the above analysis on consumers' price sensitivity, we are able to identify the advantages of deploying DR in electricity market, which not only manages to increase the social welfare by decreasing MCP but also enhances the stability of power balance by power redistribution from peak to valley.

5.2 Influence of VPP's strategy preference

Considering the risk cost involved within VPP's dispatch decision making, the factor that may affect the risk cost assessment deserves

Table 4 Clearing results of players under different cases

Case number	VPP		Player 1		Player 2	
	Output, MW	Profit, $	Output, MW	Profit, $	Output, MW	Profit, $
1	3730	17,011	2905	14,976	3345	15,016
2	3935	16,001	2842	11,633	3221	11,998
3	3730	12,838	3201	11,186	3046	9429
4	3630	12,481	3630	12,053	2664	9082
5	4112	11,570	2798	9078	3165	8617
6	4078	11,760	2780	9126	3193	8910

Table 5 Key parameters of supplementary cases

Case parameters		Price sensitivity	
		30 MW/$	50 MW/$
strategy preference	0.5 and 1.5 $/MW	case 4	case 6
	0.75 and 1.75 $/MW	case 7	case 9
	1 and 2 $/MW	case 8	case 10

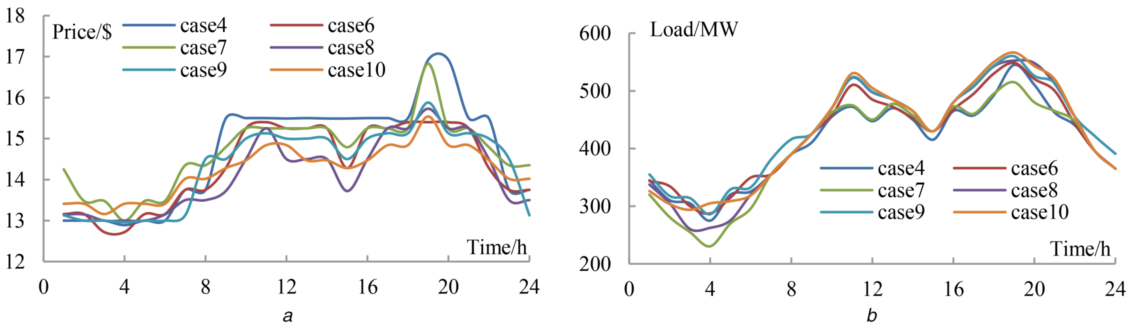

Fig. 5 *Clearing results of day-ahead market*
(a) MCP under different strategy preference, ***(b)*** Total clearing output under different strategy preference

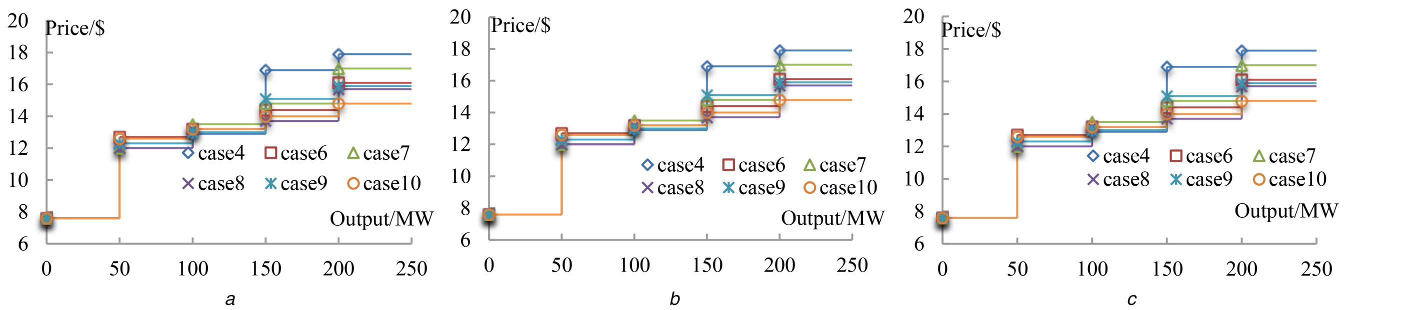

Fig. 6 *Equilibrium bidding strategies of players under different strategy preference*
(a) VPP's equilibrium bidding strategy, ***(b)*** Player 1's equilibrium bidding strategy, ***(c)*** Player 2's equilibrium bidding strategy

further discussion. As a reflection of VPP's attitudes towards potential uncertainty risk, the punish parameters for unbalanced power play an important role in the VPP's bidding strategy optimisation. In order to figure out the influence of the mentioned parameter, four supplementary cases are considered in the following analysis. The detailed parameters are listed in Table 5.

Based on the assumed cases, the clearing results of the market and the corresponding bidding strategy and profit of each participator could be summarised in Figs. 5 and 6.

According to the results presented in Fig. 6*a*, under the same level of DR involvement, the bidding strategy adopted by VPP demonstrates an obvious tendency to concentrate between specific boundaries, which in addition behaves more conservative as the strategy preference of VPP becomes more risk-averse. As rational participators in the electricity market, the bidding strategies of players 1 and 2 in Figs. 6*b* and *c* also reflect the tendency of concentration and conservation as a reaction to adapt to the strategy of VPP. Thus, the MCP in Fig. 6 incarnates a downswing as the strategies of players become risk-averse. The average MCP decreases from 14.7 $/MW in case 4 to 14.1 $/MW in case 8, which is obviously larger compared with the descent from cases 6 to 10. The reason beneath this difference is due to the effect of consumers' price sensitivity. As mentioned in Section 5.1, the bidding strategies of all players in cases 6, 9 and 10 have already become more conservative than cases 4, 7 and 8 due to the high sensitivity of price among consumers' DR. Thus, the available strategy space for cases 6, 9 and 10 is limited to a much smaller range, which confines the influence of VPP's strategy preference (Table 6).

Although the application of conserved strategy in risk control could enhance the resistance against potential risk, it also impedes the player from achieving opportunity value even when it holds the advantage of marginal participator. According to the summarised statistics in Table 7, although the output of VPP increases >10.7% from cases 4 to 8, the expected profit only increases slightly >3.8% from 12,481 to 12,956 $ as a result of the rise in risk punishment and the descent in MCP. The same situation occurs in cases 6, 9 and 10. As a conclusion to the VPP's strategy preference, the advocate of proper risk analysis in VPP's bidding strategy is essential, which could help VPP avoid unnecessary risk cost. However, the overestimation of risk would also prevent VPP from achieving its deserved profit and might even result in the low

Table 6 Key features of clearing results under different cases

Case number	Output		Price	
	PAR	Average, MW	PAR	Average, $
4	1.9	413.5	1.28	14.7
6	2.0	418.8	1.21	14.4
7	2.0	418.9	1.25	14.6
8	2.1	423.3	1.21	14.1
9	2.0	420.5	1.19	14.3
10	2.0	424.2	1.18	14.2

Table 7 Clearing results of players under different cases

Case number	VPP			Player 1		Player 2	
	Output, MW	Risk, $	Profit, $	Output, MW	Profit, $	Output, MW	Profit, $
4	3630	1831	12,481	3630	12,053	2664	9082
6	4078	2240	11,760	2780	9126	3193	8910
7	3904	2530	12,680	3385	10,947	2765	8986
8	4020	3020	12,956	2853	8667	3287	8751
9	4351	2557	11,953	2697	8911	3044	8745
10	4612	3054	12,338	2571	8674	2998	8463

efficiency operation of power resources. In order to be a rational participator in electricity market, VPP need to be risk-neutral instead of risk-averse, which requires the proper choice of risk parameters during the analysis. Based on this paper, the choice of the above parameters should refer to the MCP or historical price data and the related coefficient need to be rational based on its historical operation status.

6 Conclusion

Based on the proposed bidding procedure of electricity market, this paper presents a comprehensive operation model of VPP to integrate different sorts of DERs into a coordinated power resource, which contributes to the transformation of DERs from price-taker into price-maker. Considering the uncertainties involved within DERs, this paper proposes a scenario-based analysis model as a foundation for VPP' risk cost calculation. The main conclusions and contributions are drawn threefold.

i. (i) Under the comprehensive operation model of VPP, DERs are able to participate in electricity market more competitively and avoid the disadvantage of low capacity and geographical distribution if DERs are operated separately.
ii. (ii) Through the comparison of different scenarios, the influence of consumers' price sensitivity as well as the strategy preference of VPP is illustrated, which would play an important role in the equilibrium of marker clearing, respectively.
iii. (iii) The application of distributed algorithm into the market clearing procedure is proved to be effective, which accelerates the convergence of market clearing.

Despite of the current research progress in VPP, the influence of power network topology and power flow limits during VPP's economic decision making procedure deserves further investigation. Also, the incorporation of distribution network into the main power grid could help perfect the function of VPP in electricity market management in the future research.

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