Research on Virtual Power Plant Trading Matching Mechanism Based on Blockchain Technology

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Abstract. As an energy management and control technology, virtual power plant technology is the key technology to achieve the dual-carbon goal. In the future new power system, the multi-agent trusted transaction in virtual power plant will be more complex and challenging. The features of blockchain technology, such as information security, distributed decision-making, smart contract and tamper-proof, provide a new idea for multi-subject trusted transactions of virtual power plants. This paper focuses on the benefits maximization formed by multiple aggregators of virtual power plants and the trustworthy transaction matching efficiency. First of all, based on blockchain technology and multi-agent system integration to establish a master multi-slave hierarchical interactive control architecture; Then, based on the non-cooperative static game model, we design a P2P trusted trade matching mechanism under the demand of peer-to-peer trade. Finally, the rationality and feasibility of the strategy proposed in this paper are verified by the example analysis, which effectively enhances the matching efficiency of multi-agent transactions, improves the VPP optimization allocation ability and the overall economy.

Keywords: virtual power plant; trusted transaction; blockchain technology; hierarchical interaction; matching mechanism

1 Introduction

Under the background of China's "two-carbon" goal and the construction of a new power system [1], vigorously developing new energy represented by photovoltaic and wind power has become the only way to promote the green and low-carbon energy transformation. However, large-scale connection of Flexible Resources (FRs) such as Fengfeng to the power grid will undoubtedly affect the reliability and stability of the power grid [2]. In order to meet this challenge, Virtual Power Plant (VPP) technology has been proposed as an effective management form of aggregated FRs [3]. Based on advanced metering[4], communication and control technologies[5], it can dynamically aggregate multiple interest groups of FRs dispersed in multiple regions, multiple heterogeneity and multiple levels. Realizing multi-energy complementing[6] and market trading[7], reducing FRs operation risk and management difficulty, and promoting FRs absorption are important ways for new power systems to realize interactivity and intellectualization on the energy supply and demand side.

With the development of intelligent technology and the high proportion of FRs access, in VPP, the interaction of subjects relies on the network to achieve two-way communication, and the

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output and demand information data between subjects are easy to be tampered with by malicious attacks, resulting in errors in VPP scheduling and operation, resulting in increased costs. Moreover, frequent electric energy transaction increases significantly, which leads to the complexity of the interaction between the main body, the low efficiency of operation decision-making and the intensification of security risks. At the same time, in market transactions, VPP presents problems such as unclear identity of the subject, opaque transaction information and lack of trust of the decision-making subject.

Blockchain technology has the characteristics of distributed ledger, decentralization, collaborative autonomy, intelligent decision-making, information openness and transparency, and cannot be tampered with [8], which can well support the construction of VPP. In literature [9], She Wei et al introduced blockchain into VPP, designed an improved energy blockchain network model and applied it in VPP operation regulation, which can improve data security and storage security. In literature [10], Li Bin et al analyzed the P2P scenario in which blockchain technology is applied to VPP internal transactions. In literature [11], Zhou Buxiang et al built a master-slave game optimization method considering information network security based on the characteristics of virtual power plant and blockchain technology. Qing Yang et al in literature [12]built a VPP energy management platform based on blockchain technology to promote the energy trading activities among new energy, energy storage and flexible load within VPP. In literature[13], Chen Kailing et al proposed the operation and scheduling mode of virtual power plant in energy blockchain network. In literature[14], Ren Jianwen et al. introduced blockchain into the scheduling operation mechanism of VPP and built a practical consensus mechanism of Byzantine fault-tolerant algorithm applicable to VPP to realize a weakly centered scheduling model based on blockchain technology. Most of the above literatures focus on the combination of blockchain-based technology and VPP regulation, and do not consider the application of blockchain technology to the extensive transaction cooperation with multiple FRs stakeholders within VPP. How to ensure the smooth conclusion of transactions and maximize their respective interests is a problem to be solved.

Therefore, this paper focuses on the secure transaction matching of FRs stakeholders within VPP, and maps the latest development of blockchain technology into the interactive hierarchical architecture and functional nodes of virtual power plants. Firstly, a weakly centralized hierarchical interactive control architecture is established based on blockchain technology and Multi-Agent System (MAS). Then, based on the non-cooperative static game model, the Continuous Double Auction (CDA) transaction matching mechanism is designed under the demand of peer transaction, in order to improve the efficiency of transaction matching and the relative fairness of multi-agent transaction.

2 Virtual power plant interactive architecture based on blockchain technology and multi-agent integration

This paper studies the matching mechanism of internal resource transactions in virtual power plants, and designs the interaction architecture based on MAS, as shown in Figure 1. VPP is divided into resource aggregation layer and distributed resource layer from top to bottom. The resource aggregation layer is composed of various aggregators (Aggs). Aggs are generally classified as load Aggs, electric vehicle Aggs, comprehensive energy service providers [15], park micro-grid[16], etc. (They are collectively referred to as aggregators for easy expression). The distributed resource layer is composed of Flexible Resources (FRs) of the region to which Agg belongs. FRs mainly consist of one or more resources of Wind Turbine (WT), Photo Voltaic (PV), load users and distributed energy storage.

As a branch of artificial intelligence, MAS is a distributed autonomous computing system composed of multiple agents[17]. Through cooperative regulation of all agents, MAS can well solve the complex system operation regulation requirements and communication problems of FRs [18]. In the resource aggregation layer, an Agent is deployed for the Virtual Power Plant Operator (VPPO), each Agg and power grid company. In addition to basic operation Agent functions such as communication agent and control Agent, the agent also has transaction agent functions. Information collection and interactive decision-making related to transactions are carried out to form a multi-agent system architecture.

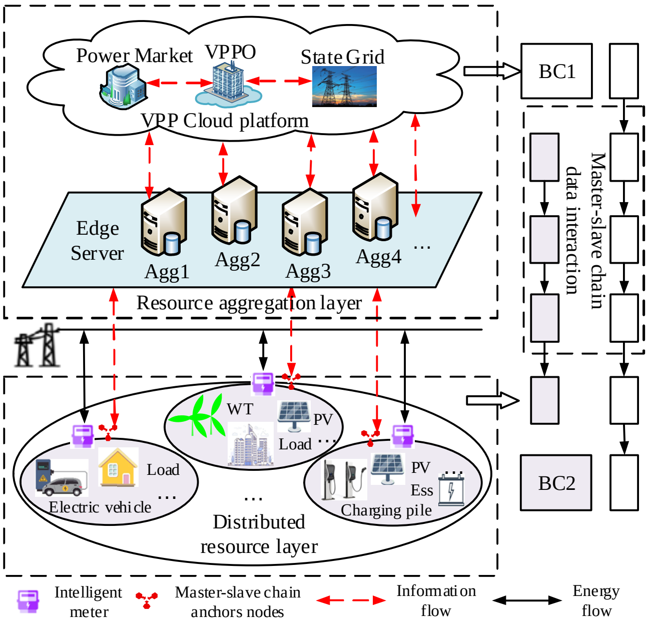

Figure 1. Virtual power plant master-slave interaction architecture

The matching mechanism of internal transaction based on blockchain includes one main chain and several slave chains. BC1 selects the alliance chain as the blockchain model of the resource aggregation layer to ensure the privacy and security of Agg interaction. Each slave chain (BC2) is constructed by the FRs of the area to which the aggregator belongs. According to the business model or demand of the aggregator, the private chain or alliance chain is adopted. The anchor nodes are designed in the slave chain, and the corresponding local computing center is taken as the base to expand to the underlying equipment of the aggregation, forming a three-dimensional flat architecture with master and multiple slave.

3 VPP multi-aggregator transaction matching mode based on blockchain

3.1 Smart contract-based multi-aggregator transaction process

Smart contract, as an event-driven code that automatically runs on the blockchain [19], can realize the automation of electric energy trading and ensure the traceability and imtampability of trading results. In order to realize the trusted trading and automatic matching settlement of VPP multi-Aggs, this paper designs a multi-Agg trading process based on smart contracts, including preparation stage, trade matching stage, contract signing stage and settlement stage. The functions contained in each stage are shown in Figure 2.

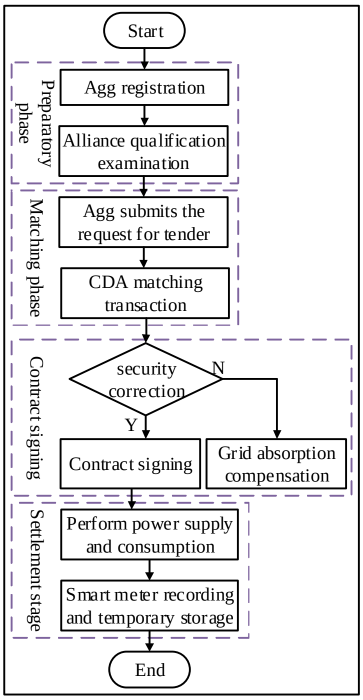

Figure 2. Smart contract-based transaction flow

（1）Preparatory stage; According to the predicted results of energy in the next period, Aggs are registered as power purchasing Aggs or power selling Aggs, and their blockchain wallet ID is bound with the smart meter ID.

（2）Transaction matching phase; Agg submits the bid application according to its own bidding strategy, broadcasts it from the chain network by the local area, and carries out matching transactions within the main chain. VPPO performs VPP internal market matching by calling the matching function and obtains the initial auction result.

（3）Contract signing stage; The initial auction results need to be calculated for security check. If the transaction does not meet the maximum power flow allowed to be exceeded, the system will be matched again or the grid will absorb compensation. After security verification, participants sign a contract to record the transaction certificate into the blockchain as much as possible.

（4）Settlement stage; Each Agg executes the power supply and absorption according to the final transaction result reached at the signing stage of the contract, calculates the income and expenditure according to the settlement method signed by the contract according to the execution of energy delivery, and updates the wallet balance of all transaction nodes in the chain. The energy interaction data is recorded and stored by smart meters deployed at multiple light nodes of the blockchain, including the main chain and all slave chains.

3.2 P2P trading mechanism based on blockchain

In this paper, the problem of maximizing the interests of multiple parties is considered. As an independent market player, the power selling Agg and the power purchasing Agg have unequal interests [20], and adopt the trading mechanism of CDA to carry out P2P transactions. VPPO and power grid develop preferential strategies to stimulate market transactions; The selling Agg decides to sell electricity to ensure maximum benefit, and the purchasing Agg decides to purchase electricity to ensure minimum cost. Based on the above, if the purchasing price is lower than the selling price, it is judged that the transaction cannot be carried out and this transaction path is closed.

In order to ensure the autonomy and benefit maximization of each Agg, the auction stage is divided into two stages ($n \leq 2$) by using the smart contract of blockchain: $n=1$ stage, each Agg submits the quotation strategy formulated according to its own benefit maximization; $n=2$ stage, the buyer and seller who have not completed the matching submit the reserve price for matching, and finally all the difference in electricity will be absorbed and compensated by the power grid. The transaction matching process is as follows.

Step 1: Every time a valid offer is received, the block chain system will update the power selling queue and the power purchasing queue respectively according to the increasing order and decreasing order of the offer. If the offer is the same, it will sort and match according to the transaction credit value.

Step 2: Compare the lowest offer in the power selling queue with the highest offer in the power buying queue by ordering the purchase queue. If the conditions are met, the selling Aggj matches the purchasing Aggi, and the transaction amount is the minimum value of both. Otherwise, the remaining unmatched buyers and sellers will move on to the next round of trading.

Step 3: Check the security of the matched transaction. If the transaction meets the constraints, it is matched successfully. Otherwise, cancel the match

Step 4: Judge whether the matching time is up to or whether two rounds of matching have been completed. If yes, the Agg is not successfully matched and the power grid will carry out absorption compensation.

3.2.1 CDA mechanism quotation strategy and transaction price formulation

In order to regulate the malicious quotation behavior of all Aggs participating in the transaction and ensure the timeliness of the quotation [21], the first quotation strategy and reserve price calculation program are built into the smart electricity meter of each Agg. The first offer is the basis for Agg to match in the first round of transaction. If this round of transaction is unsuccessful, the second round of matching will be carried out with the reserve price, and finally the power grid will absorb and compensate the power difference of the aggregator. The reserve price of the selling Agg is set according to the relationship between the generation cost and the generation capacity. The reserve price of the purchasing Agg is set according to the relationship between the energy utility and the net load evaluated by the purchasing Agg, and is determined according to the unit energy utilization efficiency. The first round quotation of Agg is as follows:

$$\lambda_i(t) = \lambda_0(t) + \mu \frac{P_{i,t}^{load} - P_{i,t}^{pre}}{P_{i,t}^{pre}} \left[\lambda_{grid}(t) - \lambda_0(t)\right] \tag{1}$$

$$\lambda_j(t) = \lambda_{grid}(t) - \frac{P_{j,t}^{pre} - P_{j,t}^{load}}{P_{j,t}^{pre}} \times \left|\lambda_{grid}(t) - \max\left\{\lambda_0(t), c_j\right\}\right| \tag{2}$$

Where:$\lambda_i(t)$、$\lambda_j(t)$ They are respectively electricity purchasing Agg and electricity selling Agg;、$\lambda_{grid}(t)$、$\lambda_0(t)$Are respectively the selling price and the on-grid price; $\mu \in (0,1)$, Indicates the power purchasing Agent preference, In this paper, 0.5 is taken.; c_j Is the power generation cost of aggregator j; $P_{j,t}^{pre}$ 、 $P_{j,t}^{load}$ Are the predicted output and load values of distributed energy of aggregator j in time period t;

The final transaction price uses the transaction credit value of Aggs to construct the transaction quality evaluation coefficient to encourage all Aggs to actively participate in the internal transaction of VPP and ensure the performance of the contract. The transaction price is as follows:

$$\lambda_{i,j}^{t,n} = \xi_{i,j}(t)\lambda_i + \left(1 - \xi_{i,j}(t)\right)\lambda_j, \lambda_j \le \lambda_i \tag{3}$$

$$\xi_{i,j}(t) = \frac{R_{E,i}^{s}(t)}{R_{E,i}^{s}(t) + R_{E,j}^{b}(t)} \tag{4}$$

Where:$\lambda_{i,j}^{t,n}$: Transaction price; $\xi_{i,j}(t)$: Transaction quality evaluation coefficient; $R_{E,j}^{s}(t)$, $R_{E,i}^{b}(t)$: Agg trading credit value of selling power and Agg trading credit value of purchasing power;

3.2.2 Trading reputation establishment

Due to the heterogeneity of FRs, the energy regulation capacity and actual power fluctuation of different resources are different[22]. In order to ensure the stability of the overall power level of VPP and the orderly conduct of its internal transactions, the transaction quality evaluation coefficient is constructed based on the transaction completion situation to encourage VPP to improve the transaction completion degree to obtain greater bidding advantages, as shown in Equation (5).

$$a_{i,t}=\begin{cases}1, & \left|\dfrac{P_{i,t}^{ac}-P_{i,t}}{P_{i,t}}\right|\leq 2\% \\ \dfrac{P_{i,t}^{ac}}{P_{i,t}}, & \left|\dfrac{P_{i,t}^{ac}-P_{i,t}}{P_{i,t}}\right|>2\% \end{cases} \tag{5}$$

Where:$a_{i,t}$ Is the transaction evaluation coefficient，$P_{i,t}^{ac}$ Actual delivery value，$P_{i,t}$ Is the contract quantity；2% To allow the deviation of the outgoing line；

The credit value of power trading entities is the result of long-term participation in market transactions, which is updated with the trade evaluation coefficient $a_{i,t}$in a 24h cycle

$$\begin{cases} R_{E,i}(t)=R_{E,i}(t-1)+\Delta R_{E,i}^{+}(t), a_{i,t}\geq a_{i,t-1} \\ R_{E,i}(t)=R_{E,i}(t-1)-\Delta R_{E,i}^{-}(t), a_{i,t}\leq a_{i,t-1} \end{cases} \tag{6}$$

$$\begin{cases} \Delta R_{E,i}^{+}(t)=\left(a_{i,t}-a_{i,t-1}\right)^{2}\left(1-R_{E,i}(t-1)\right) \\ \Delta R_{E,i}^{-}(t)=\left(a_{i,t}-a_{i,t-1}\right)^{2}R_{E,i}(t-1) \end{cases} \tag{7}$$

Where，$R_{E,i}(t)$：The trading value of the current trading cycle；$R_{E,i}(t-1)$：Trading credit value in the last cycle

；$\Delta R_{E,i}^{+}(t)$、$\Delta R_{E,i}^{-}(t)$：The evaluation coefficient of trade quality in the current trading cycle is higher than the reward value of trade reputation in the previous cycle and the penalty value in the opposite case；

4 Case study

4.1 Basic setup

In order to verify the effectiveness of the VPP matching mechanism proposed in this paper, a VPP distributed transaction experimental platform was built in the Win10 64bit system. The development of VPP internal transaction blockchain was implemented in reference[22]. By publishing the chain code to Hyperledger Fabric, And based on Java SDK to create a local client to achieve.

Based on the IEEE64 node system, it is divided into 6 Agg regions, and each Agg field location is located in the adjacent region, and its load characteristics are significantly different. Set the allowable voltage offset range to 0.95p.u. to 1.05p.u. The transmission power limit of the link line between the two regional aggregators is 10MW. Agg1-2 distributed energy includes PV, WT; Agg3 distributed energy contains PV, and Agg4 distributed energy contains

WT. Agg5-6 distributed energy includes PV and WT; The WT capacity of each Agg is 500kW; PV capacity is 300kW; Energy Storage System (ESS) capacity is 200kW; In order to simplify calculation, FRs of the same type have the same constraints, and the prediction curve is shown in Figure 3-Figure 5.

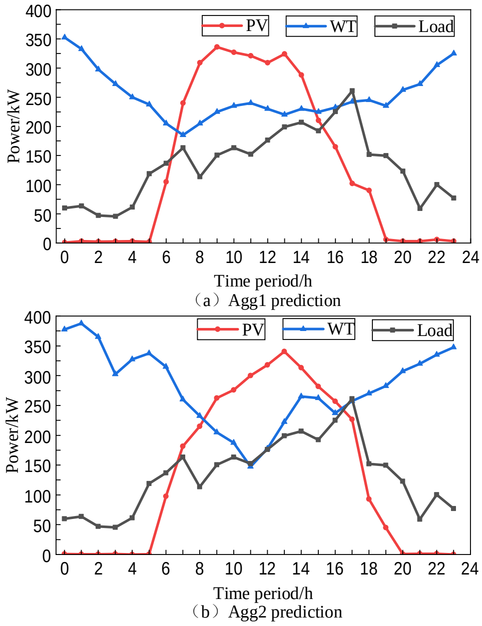

Figure 3. Predicted value of Agg1-2

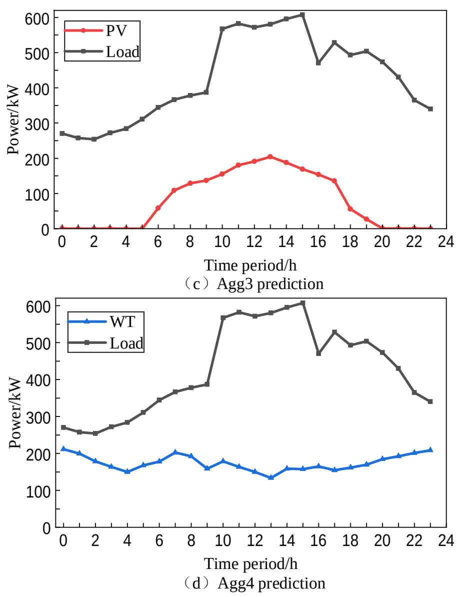

Figure 1.Predicted value of Agg3-4

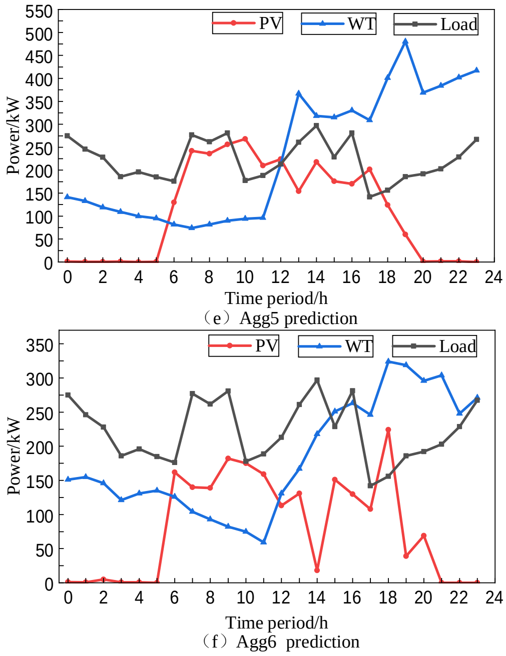

Figure 2. Predicted value of Agg5-6

4.2 CDA matching simulation and analysis

4.2.1 Matching simulation setting

In addition to 6 Aggs in the main chain of resource aggregation layer, VPP dispatching center node and power grid node are also arranged, and 8 nodes have the function of consensus. This case analysis aims at Aggs. It is assumed that VPPO and grid nodes can record correctly when participating in bookkeeping, and there is no communication delay and other problems. In this paper, two periods of 01:00-02:00 (t=2) and 12:00-13:00 (t=13) were used to verify the matching of VPP main chain CDA. The parameters of TOU are shown in Table 1. The quotation information of the two parties during t=2 and t=13 is shown in Table 2 to Table 5.

Table 1. Time-of-use price parameter

Time period	Electricity sale price	Electricity purchase price
23:00-07:00	0.38	0.24
07:00-11:00 14:00-18:00	0.57	0.38
11:00-14:00 18:00-23:00	0.86	0.65

Table 2. The electricity sale information of producers(t=2)

Agg	Offer	Reserve price	Electricity sold	Reputation value
Agg	Offer	reserve price	electricity sold	reputation value
Agg1	0.318	0.3	282.5	0.846
Agg2	0.32	0.315	324.2	0.724

Table 3.The purchasing information of consumers(t=2)

Agg	Offer	Reserve price	Electricity sold	Reputation value
Agg3	0.318	0.34	234.22	0.965
Agg4	0.32	0.356	58.34	0.782
Agg5	0.318	0.333	217.6	0.829
Agg6	0.331	0.356	90.4	0.706

Table 4. The electricity sale information of producers(t=13)

Agg	Offer	Reserve price	Electricity sold	Reputation value
Agg1	0.72	0.695	318.7	0.823
Agg2	0.733	0.673	319.26	0.755
Agg5	0.72	0.658	75	0.763
Agg6	0.755	0.673	31	0.657

Table 5. The purchasing information of consumers(t=13)

Agg	Offer	Reserve price	Electricity purchase	Reputation value
Agg3	0.713	0.736	285.6	0.922
Agg4	0.76	0.78	421.68	0.753

4.2.2 Matching result analysis

The internal matching results of VPP are shown in Table 6-Table 7. From 01:00 to 02:00, it can be seen that the electricity sold and purchased by Aggs are similar. After the first round of matching, Agg2 has some remaining electricity, and all the other buyers and sellers have successfully auctioned off the electricity demand, without the need for the second round of matching. At this moment, Agg3 and Agg5 are both buyers and offer the same price. Because Agg3 has higher trading credit value, Agg3 is superior to Agg5 in matching sort. After the end of the auction transaction, Agg2 has a small amount of electricity left, which is sold to the power grid at the grid feed-in price. From 12:00 to 13:00, it can be seen that the trading market forms a buyer's market, and the electricity sold is greater than the electricity purchased. After the first round of matching, the buyer Agg3 failed to match, because its price was lower than the price of the seller Agg1 and Agg5, so the second round of matching was carried out, and Agg3 settled at the reserve price. The quotation of Agg1 and Agg5 is the same, but Agg1 has a higher credit value, so Agg1 gives priority to matching transactions. Agg5 sells the remaining electricity to the grid. After two rounds of matching, all Aggs meet the corresponding requirements.

Table 6. Transaction matching result(t=2)

Matching	Electricity Sold(kW/h)	Electricity purchase (kW/h)	Turnover (kW/h)	Surplus (kW/h)	Trading reputation		Transaction factor	Transaction offer (yuan/kWh)		transaction price (yuan/kWh)
1-6	282.5	90.4	90.4	192.1	0.846	0.706	0.545	0.318	0.331	0.325
1-4	192.1	58.34	58.34	133.76	0.846	0.782	0.520	0.318	0.32	0.319
1-3	133.76	234.22	133.76	100.46	0.846	0.965	0.467	0.318	0.318	0.318
2-3	324.2	100.46	100.46	223.74	0.724	0.965	0.429	0.32	0.318	0.320
2-5	223.74	217.6	217.6	6.14	0.724	0.829	0.466	0.32	0.318	0.319
2	6.14		—		0.724		—			0.240

Table 7. Transaction matching result(t=13)

Matching	Electricity sold(kW/h)	Electricity Purchase (kW/h)	Turnover (kW/h)	Surplus (kW/h)	Trading reputation value		Transaction factor	Transaction offer (yuan/kWh)		transaction price (yuan/kWh)
6-4	31	421.68	31	390.68	0.657	0.753	0.466	0.755	0.76	0.756
2-4	319.26	390.68	319.26	71.42	0.755	0.753	0.501	0.733	0.76	0.747
1-4	318.7	71.42	71.42	247.28	0.823	0.753	0.522	0.72	0.76	0.741
					n=2					
1-3	247.28	285.6	247.28	38.32	0.823	0.922	0.472	0.72	0.736	0.728
5-3	75	38.32	38.32	36.68	0.763	0.922	0.453	0.72	0.736	0.727
5	36.68				—					0.650

The CDA matching mechanism of the resource aggregation layer can realize the peer-to-peer and trusted transactions of multi-agents and maximize their respective interests. Meanwhile, the friendly interaction between the internal price of VPP and the price of large power grid can effectively improve the power generation profit of Agg and reduce the electricity cost of users.

4 Conclusion

In this paper, the multi-stakeholder transactions within VPP face problems such as unclear identity of the subject, opaque transaction information, low efficiency of operational decision-making and increased transaction security risks under the new form. Firstly, based on blockchain technology and integration of MAS, a multi-stakeholder hierarchical interaction architecture is established for multi-Aggs within VPP. Then, based on the non-cooperative static game model, a weak centralized power CDA matching mechanism suitable for multi-Aggs in VPP is designed to realize multi-Aggs trusted trading in VPP. Through example analysis, the VPP distributed trading platform is built, and the CDA matching trading process is analyzed, which can realize the multi-agent peer-to-peer trusted trading and maximize their respective benefits.

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