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REVIEW

Research on key technologies of P2P transaction in virtual power plant based on blockchain

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Abstract

It is a critical part of increasing renewable energy accommodation by using virtual power plant (VPP) to attain carbon neutrality. However, VPP applications primarily consider VPP's participation in power market transactions as a whole and rarely consider the transaction interaction between internal resources. VPP's internal resources complement each other organically, and blockchain technology for distributed transactions has incorporated points. In this article, the authors undertake a study and examine the P2P scenario of VPP internal transactions in light of the issues experienced by DERs transactions. Next, the authors analyse the consensus mechanism, smart contract, inter-blockchain technology, and game theory, and how to apply them in the P2P scenarios of VPP internal transactions. Further, the authors design the function of the DER transaction system, which lays the foundation for the realisation of the system in the future. Finally, the authors conclude that the potential of blockchain technology in P2P transactions between internal entities of the VPP is significant and warrants further investigation.

KEYWORDS

blockchain, consensus mechanism, inter-blockchain technology, P2P transaction, smart contract, virtual power plant

1 | INTRODUCTION

1.1 | Motivation and related work

China must rapidly create a low-carbon, clean, safe, and efficient energy system to meet its 2030 objective of peaking carbon emissions and becoming carbon neutral by 2060 [1, 2]. All types of renewable energy, such as solar energy, wind power, and hydropower, must be widely developed [3]. However, because most renewable energy is unpredictable and uncertain, it brings a lot of peak shaving and valley filling pressure to the power system. By coordinating numerous distributed energy sources to engage in power system operations, virtual power plant (VPP) plays an important role in renewable energy accommodation. Jibei North Power Trading Centre submitted the Virtual Power Plant Flow Draft International Standard (Virtual Power Plants: Use Cases) to IEC on Sept.18, 2020 [4]. VPP's technological advancements and application successes in China have been described and condensed. The participation of VPP in P2P trading of new energy power is regarded as one of the development directions of the new power system in the White Paper of China Southern Power Grid Corporation's Action Plan for the Construction of New Power System, released in May 2021 [5].

The critical factor that affects the security and efficiency of transactions in VPP is how to coordinate DERs and controllable load. In the current electricity markets, most of them use a centralised approach. However, the centralised coordination method may increase transaction security risk and processing time, so some decentralised methods are preferred [6–8].

Some experts and scholars have proposed several blockchain applications in VPP [9–11]. Combined with electricity trading, the business structure and transaction mode of VPP can be established in the blockchain environment, and the VPP energy certification and certificate transaction mode based on blockchain technology can be designed [12]. By using PBFT and equal consumption micro-growth rate model, the economic benefits of the VPP can be high-speed improved [13]. It can be balanced between different agents for specific consensus mechanisms to improve the robustness of the Security Constrained Economic Dispatch (SCED) algorithm [14]. A blockchain network model suitable for the energy and electric power industry is studied, and then the corresponding VPP scheduling model is designed [15]. Considering the interoperability requirements between blockchain, some key technologies of data interaction of heterogeneous blockchain in the multi-energy system are analysed to support complex energy transactions [16] smart contracts can be written on the Ethereum blockchain platform to design P2P energy transaction schemes for VPP [17, 18]. For the application of game theory, when designing the distributed strategy update algorithm (DSUA) based on a distributed power dispatch algorithm (DPDA), the DSUA considers the situation of suppliers' alternate or simultaneous update of bids. Game theory analysis and simulation can show the closeness of supplier bids to the Nash equilibrium [19].

Energy blockchain technology in DER transactions is widely applied. There are few studies on the application of inter-blockchain technology in DER transactions, but there are no relevant research results on the DER trading system within VPP in which blockchain technology participates.

1.2 | Contribution

This paper applies the latest developments of blockchain to P2P energy transactions within virtual power plants. The major contributions of the article are summarised as follows.

(1) Comparing and sorting out different blockchain consensus algorithms applicable to the DER transactions. Besides, the application mode of the VPP smart contract and inter-Blockchain solution is studied.
(2) We have designed a DER P2P transaction system and introduced a blockchain-related functional design to support the future application of VPP interaction.

2 | DER TRADING CHALLENGES AND APPLICABILITY ANALYSIS

2.1 | DER trading challenges

The DER trading mechanism is constantly changing as the market changes. With the rapid development of information and communication technology, it will produce a lot of new market entities, that is, power generation enterprises, aggregators, third-party energy service providers etc. There are enormous challenges ahead for distributed VPP transactions, especially in an untrusted environment [20].

(1) Various market entities

Even though the geo-distributed owners of DERs show a strong willingness to participate in the transaction of VPP, the crisis of confidence makes them distrust each other [21, 22]. Additionally, the diverse requirement of information security for owners complicates the transaction of VPP. Solving the crisis of confidence and security of transaction information is of strategic importance to the grid.

With the deregulation of the energy trading market in China, increasing DERs participate in grid-interactive projects. For instance, the ancillary service market managed by State Grid based on the Intelligent Vehicle Networking Platform is expected to connect more than 1 million charging piles and serve 3 million electric vehicles. To enable the transaction of distributed energy and to enhance the management of the market, the National Development and Reform Commission (NDRC)and National Energy Administration released a series of policies, where DER projects can choose to sell electricity nearby within 110kV voltage level, and the buyers and sellers can independently decide the transaction mode and transaction price. Given this context, the grid and the owners of DERs would break the 'wall of selling electricity'. Those policies reconstruct the original rules of power trading and that of the power market [23].

(2) Electric power market risk

Compared with the traditional power market, the credit risk in the P2P energy market will increase sharply. From the perspective of the market mechanism, the lack of government endorsement in the market makes profit-seeking users have a chance to engage in vicious competition at the trade fair. DER aggregators have higher choices, which provides space for market subjects to default [24]. All discourages further transactions with DERs, and the grid will ultimately have to pay for those risks. However, without proper trading mechanism design, participants may engage in dishonest behaviour, which further leads to a potential crisis of confidence and even market failure [25].

(3) Complex business scenarios

Some regions or provinces establish different energy trading rules of DERs. However, these rules are revised frequently to match the dynamic trading demand of DERs, which means that the share of energy transaction information between regions would be difficult [26]. To make unified management of geo-distributed DERs, cross-region interaction schemes and trading rule contracts should be established to solve the above problems.

2.2 | Applicability analysis

The following Figure 1 shows the VPP architecture based on blockchain. The VPP control centre carries out business interaction with the dispatching centre and the power market at the upper level, and the lower level carries out business interaction with distributed resource aggregators such as electric vehicles, energy storage equipment, and controllable loads. Each node in the VPP blockchain network has its own

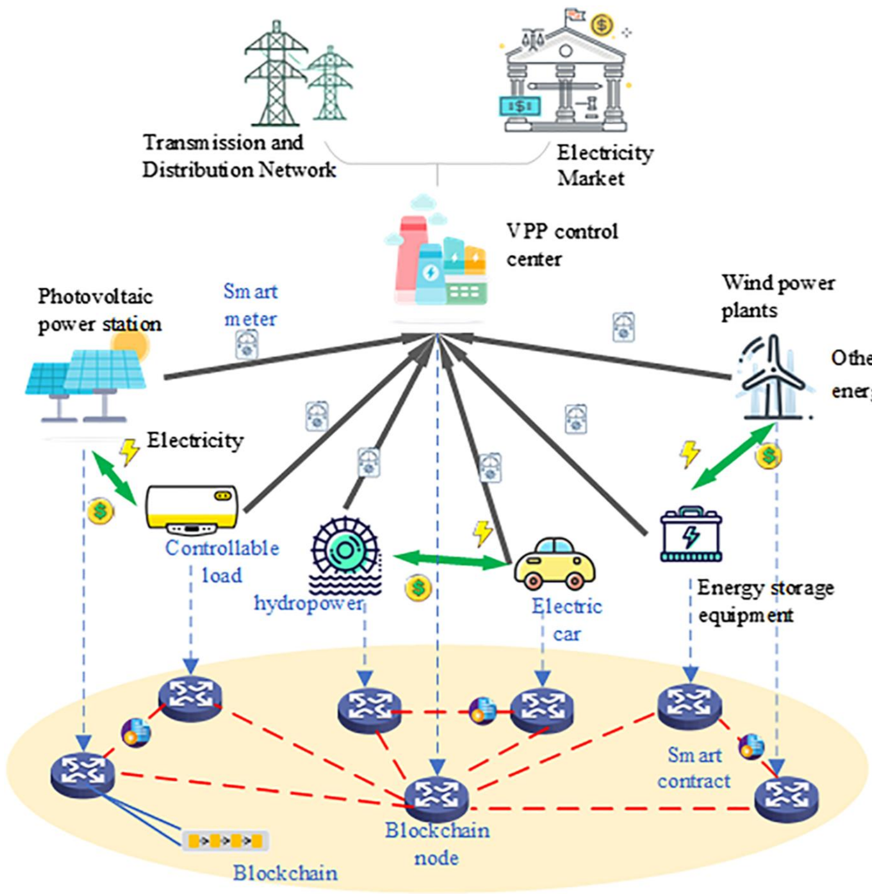

FIGURE 1 Blockchain-based virtual power plant (VPP) architecture

distributed ledger. The VPP control centre is responsible for maintaining the status of each node and collecting transaction requests, transaction records, and other tasks. Blockchain can form a complete and reliable VPP distributed database, making its distributed ledger impossible to tamper with.

It can make up for the deficiency of VPP with a fully decentralised structure. The applicability of blockchain technology in virtual power plants is mainly as follows:

(1) DERs' Joint Maintenance and Supervision. The ledger data in the blockchain has the right to common supervision and access, and the blockchain transaction network made of DERs has the right of common read and write access to data, which greatly ensures the security and transparency of transaction data.
(2) Automating P2P transactions. Smart contracts, which can be triggered by an event and execute related activities according to specified rules without the supervision of a third party, can be written in the business system. Automatic matching and transaction settlement are realised through contract execution, drastically shortening the profit cycle of distributed energy and enhancing transaction efficiency [27, 28].
(3) Realising service convergence between different chains. The scalability and compatibility of a fully decentralised VPP will be optimised by inter-blockchain technology [29]. While applying blockchain to internal transactions, different underlying chains can be adapted according to different transaction attributes. Inter-blockchain technology can realise business integration between different chains.
(4) Increasing fairness in the distribution of benefits. In decentralised networks, how fairly distributing the profits from node transactions is the key to improving the enthusiasm for distributed energy participation and response [30].

3 | KEY TECHNOLOGIES OF BLOCKCHAIN APPLIED TO THE INTERNAL TRANSACTION OF VPP

3.1 | DER consensus mechanism

In the application of blockchain technology in the P2P transaction of VPP, the VPP control centre controls the aggregation of DER data, the data records in the traditional VPP are centralised. The transaction data of the generation side and the demand side will be transferred to the main station for recording. Still, the data is unsupervised and easily tampered with internally. The appropriate accounting node will be selected to synchronise the transaction information in the DER transactions that join the blockchain consensus mechanism. Although it is a P2P transaction, all nodes in the blockchain can jointly supervise the transaction and realise the real-time update of the records of the whole network. As for the choice of consensus mechanism in VPP, we should consider the requirements of decentralisation degree, some security and resource consumption issues in a specific environment. As shown in Table 1, for comparison of some common consensus algorithms, the proof consensus algorithm should be preferred in the scenario with a high requirement for decentralisation such as Proof of Work (PoW) [31], Proof of Stake (PoS) [32], Proof of Majority (PoM) [33], Proof of Authority (PoA) [34], Proof of Contribution (PoC) [35] etc. It can also adapt to different scenarios to improve the specific algorithm. For example, it can refer to the largest shareholder in the PoS algorithm as the accounting node. The VPP can select the node with the largest power generation and consumption as the accounting node to achieve the consensus accounting of the whole network [36]. Considering resource consumption, consensus algorithms such as PoS and DPoS should be considered the main priority. However, there are some security problems in using proof algorithms, such as a 51% attack [37], Solar Eclipse attack on PoW, selfish mining and rights centralisation, and DDoS attack on disinterested DPoS of PoS. In the case of high-security requirements, another type of consensus algorithm, distributed consensus algorithm, should be considered. The standard algorithms are Practical Byzantine Fault Tolerance algorithm (PBFT) [38], Paxos algorithm [39], Raft algorithm [40], Gossip algorithm [41], Zab algorithm [42], and so on. However, the degree of decentralisation of this kind of algorithm is not as good as that of proof algorithms, so we should consider the requirement of centralisation when using this kind of algorithm. Since most application scenarios within VPP should first consider security, reliability, and capacity issues. For example, PBFT can solve Byzantine problems and accommodate the wrong nodes. The raft algorithm can adjust the faulty nodes in a complex network environment and ensure the balance of the whole network based on the security of nodes with odd numbers.

VPP operators need to consider the DERs requirement from different entities and use different consensus algorithms, the following Figure 2, combined with inter-blockchain technology, we can design given the hierarchical partitioning of the VPP internal consensus solution. In such a situation, after reaching an agreement with the master node's consensus node, it can enter or leave the chain at any time without affecting the total transaction.

3.2 | Smart VPP contract

The demand and generation sides of traditional VPP internal transactions are hard to execute P2P transactions safely. A centralised node needs specific procedures to collect demand information from each trading side. Throughout the process, the third-party supervision node needs to assure information security so that the execution efficiency is very low. ‘Event triggering’ is used to carry out smart contracts. The logic of P2P transactions is equipped with different smart contracts and can be triggered automatically [44]. All transaction processing and preservation methods, as well as a comprehensive state machine for accepting and processing multiple smart contracts, are included in smart contracts. Each contract's state machine and trigger condition are traversed by the smart contract regularly, and when it meets the trigger condition it is pushed into the queue to be validated. The to-be-confirmed contract will be sent to each node for confirmation.

P2P secure transactions, which apply blockchain, can be realised without the participation of a third party. DER aggregators can be regarded as blockchain nodes. After the VPP aggregator authenticates the identity of each DER node and before the opening of the internal trading market, the demand side and generation side resources can sign contracts to collect the demand for DERs, formulate smart contracts, and store them in the chain. The transaction process will automatically generate information and store it in the blockchain according to the conditions stated in the smart contract, which will settle in real-time in the form of e-CNY. Compared with the traditional trading market, the smart contract simplifies the transaction process, which plays a corresponding role in the process of identity authentication, subject matching, audit, and settlement, improves trading efficiency, and ensures trade security.

Take P2P transactions of EVs (Electric Vehicles) [45] as an example (Figure 3). Emergency transaction requests can be sent to the P2P blockchain trading platform immediately. The platform keeps a smart contract signed by the EV user and indicates the demand. After the platform receives the demand information sent by the emergency demand user, if users meet the requirements, they will automatically match the transaction. The whole network supervises the transaction process and keeps it in the chain. In this way, users with charging and discharging demand can give up the right to use energy without an urgent need, and the whole market can achieve efficient P2P transactions.

3.3 | VPP combination chain technology

In P2P DER transactions, several blockchains can be used depending on the transaction attributes. If there are different data chains, the blockchain's data-sharing and value transfer will become unreliable, which makes business circulation difficult to realise. Inter-blockchain technology enables business value accommodation between different networks while also improving blockchain scalability. Using combination blockchain technologies allows for the flexible interaction of resources between chains while yet allowing for efficient transaction processing.

The following Figure 4, shows the transaction diagram of DERs based on the combination chains. Based on Polkadot's idea [46] and different internal resource attributes, this article divides VPP into a demand Relay chain, DG (Distributed Generation) Relay chain, and energy storage Relay chain. Each VPP chain is composed of some Parachains and a Relay chain [47]. The inter-blockchain [48] P2P transaction design can be applied to the transaction of large multi-energy and realise the

TABLE 1 Comparison of consensus algorithms for virtual power plant (VPP)

Type	PoX algorithms				Distributed consistency algorithm		
Algorithm	PoW	PoA	PoS	DPoS	PBFT	Paxos	Raft
Projects	Bitcoin/Litecoin/Bitcoin-NG/GHOST/Ethereum	PoA.Net work	Peercoin/Cardano/Blackcoin	EOS/Bitshare	Hyperleger Fabric/Cita/ripple	WPaxos/Chubby/Hypertable	Fabric/Alluxio/etc
Hash Computation	H	L	L	L	H	H	L
Security	M (51%attack, eclipse attack, selfish mining)	M (Malicious nodes, privacy issues)	H (51% attack, no interest [43])	L (power centre, DDoS attack)	H (<33.33% common node/<33.33% common node/<20% common node	H (no malicious node)	H (no malicious node)
Throughput/TPS	<20TPS	<400TPS	≥25TPS	>300TPS	>1000TPS	>5000TPS	>5000TPS
Block generation time/s	300s	5s	64s	3s	0.5s	2s	2s
Trade confirmation Time/s	60s	10s	30s	10s	Immediately confirm(1s)	1s	1s
Fault tolerance	1/2	1/2	1/2	1/2	1/3	0	0
Divaricating	H	H	H	N	N	L	L
Delayed	H	L	H	L	L	L	L
Scalability	L	L	L	H	H	H	H
Energy consumption	H	H	L	L	L	H	L
Applicable scenario	Large-scale VPP transactions within the campus	The degree of decentralisation is high and the scale is small	Large-scale VPP transactions within the campus	Large-scale VPP transactions within the campus	Complex network trading environment	Complex network trading environment	Complex network trading environment

Note: H(High), L(Low), N(Normal).

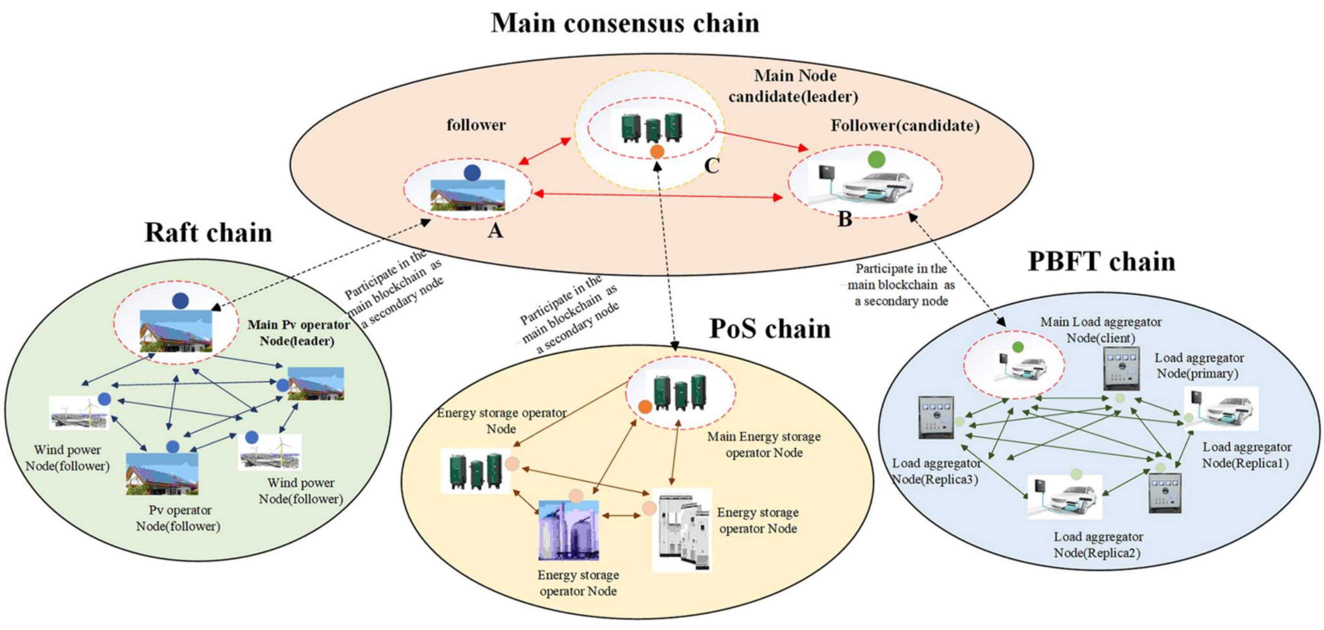

FIGURE 2 Schematic diagram of composite consensus mechanism

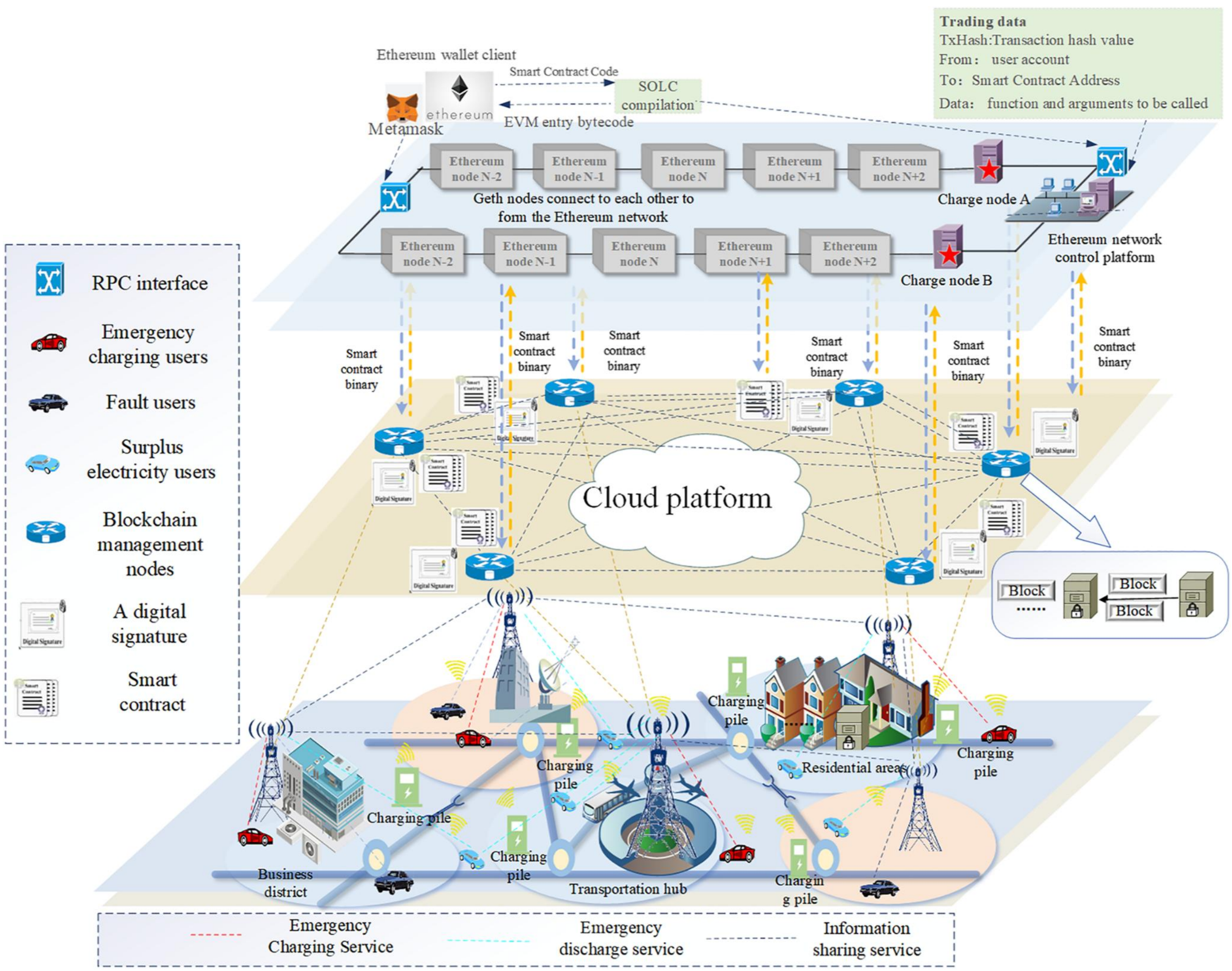

FIGURE 3 P2P transaction diagram of electric vehicle based on smart contract

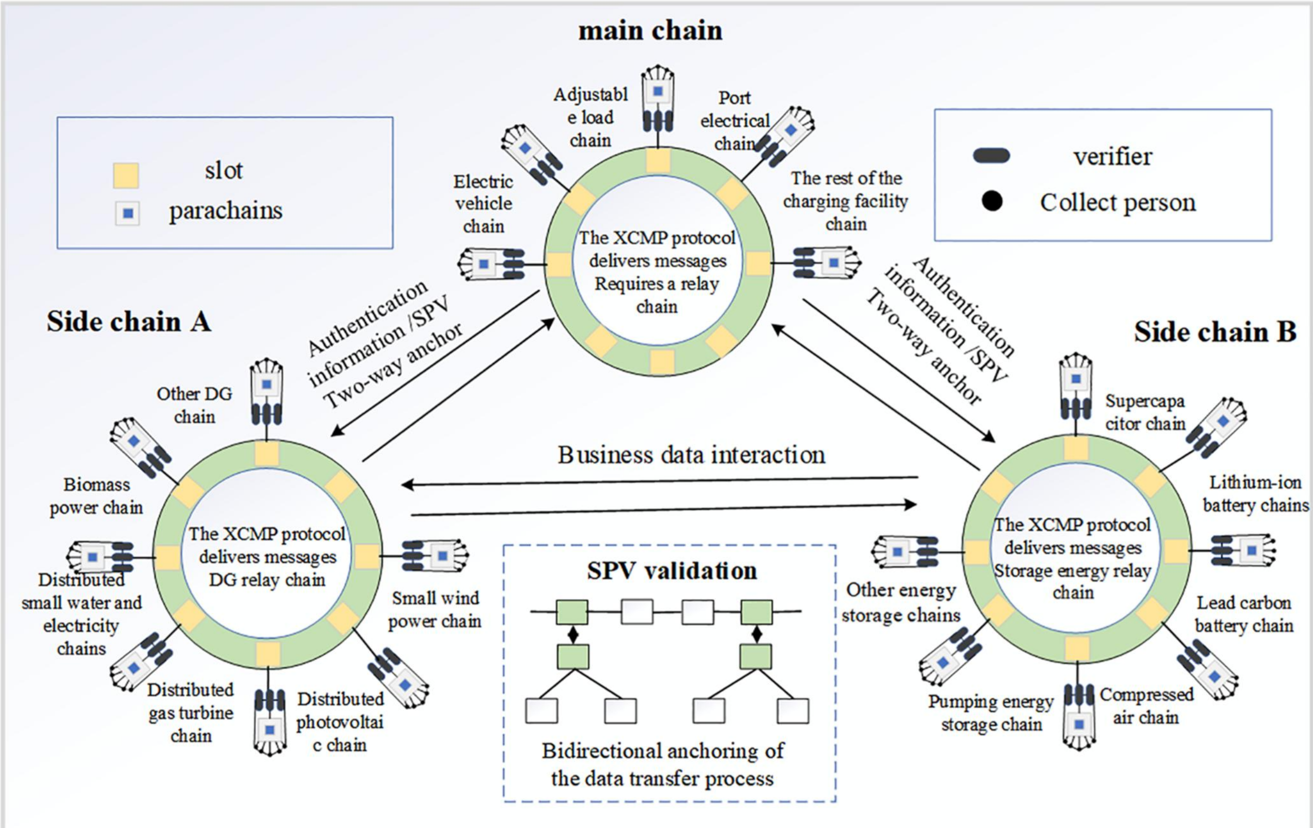

FIGURE 4 Transaction architecture diagram of virtual power plant (VPP) based on composite chain

interoperability of the internal resource chain of the VPP. In the combined chain architecture, the slots in the Parachain can ensure that each transaction ledger is stored and the demand (generation data is updated) in real-time. Each Relay chain uniformly manages the operation and consensus of the Parachains in the region, and all the light nodes are directly integrated into the Relay chain. All data, including the main chain and side chain [49] data, need to be verified by the Relay chain before data sharing (Cross Chain Message Passing Protocol Data Transfer).

Different participating entities will receive the demand and price information. Each DER can also participate in bidding as a parallel thread. When parallel DERs want to participate in energy trading, they can take part in the auction, which will take place in each relay block of the DG chain, and send authentication information to the main chain after passing the side chain verification. SPV bi-directional anchoring technology is applied to realise the secure transaction of each chain resource through multiple verifications. In addition, under the combination chain system, in the smart contract, we can further introduce some authority mechanisms, reward/punishment mechanisms, and supervision audit schemes in the relay chain to promote the enthusiasm of internal P2P traders.

In summary, the inter-blockchain technology supports data flow and contract call between homogeneous (heterogeneous) blockchain and ensures contract call data flow and atomicity through multiple relay-chain verifications.

3.4 | Benefit distribution of DERs based on game theory

Research on VPP mainly focusses on overall external characteristics and VPP participation in market bidding. Few studies have considered the P2P coordination strategy, operation mechanism, and individual benefit analysis between internal DERs of VPP [50–52]. When VPP participates in bidding transactions in the power market, VPP operators issue scheduling orders to DSO and coordinate and control DERs. In the settlement, the power market will issue the confirmed cost of products, and after the settlement, VPP operators will distribute interests to DER. Figure 5 is the block diagram of the bidding transaction.

In the absence of any incentive mechanism, especially when the internal DER belongs to different investment subjects, it is challenging to truly realise centralised scheduling and complementary operation. Therefore, considering the market mechanism of complementary process inside VPP and the diversified interest demands of different participants, a new interest distribution scheme is designed by combining the economics technology in blockchain, namely the game theory, to improve the efficiency of P2P transactions on both sides inside the VPP.

From the perspective of game theory, the distributed consensus and transaction rights of blockchain are consensus systems that achieve Nash equilibrium [53, 54]. Game theory

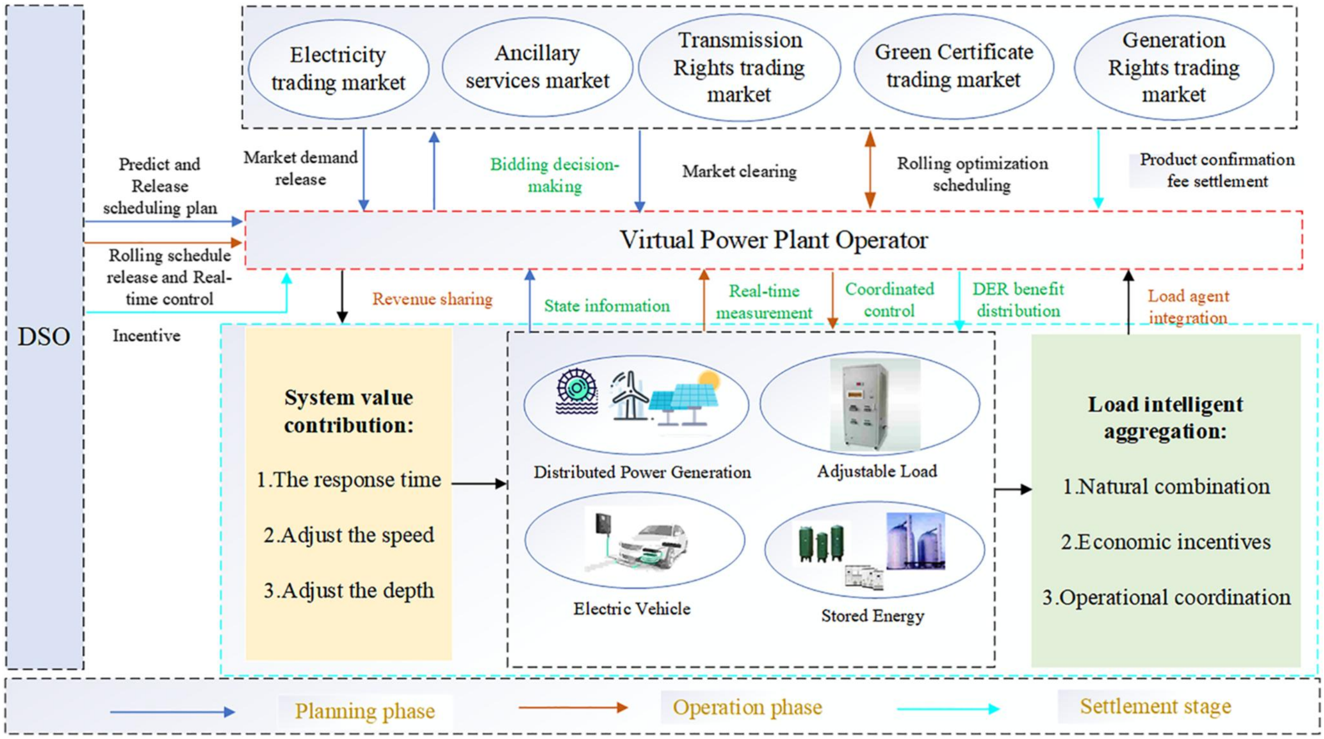

FIGURE 5 Block diagram of virtual power plant (VPP) bidding transaction

can develop some incentive mechanisms to prevent nodes from improper execution or attack. Game theory can be divided into Cooperative game and Non-Cooperative game. The Non-Cooperative game emphasises maximising self-interest, and the Cooperative game emphasises collectivism, group rationality, fairness, and justice. Considering the internal bidding of DERs in the VPP, if there are some conflicts of interest among various controllable resources in the internal reserve market, the Non-Cooperative game is preferred. Suppose we do not consider the internal bidding of VPP, but participate in the market bidding as a whole to distribute the benefits internally. In that case, we should prioritise using the cooperative game to maximise the output of DERs. When considering the internal benefit distribution of VPP, game theory should be based on the characteristics of DG output, generation cost, expected profit, and other needs, based on the features of conflict of interest and self-benefit of various DG investors in the market competition, and the information of each DG is not entirely public, to design a bidding scheme of controllable DG participating in internal reserve market based on Non-Cooperative game theory. Typical models of incomplete information games are mainly the Cournot Model, Stackberg Sequential game Model, Supply Function Model etc. [55]. By comparison, the electricity market price is usually determined by the total market demand and the supply function of each producer, so the supply function model is often considered in the internal bidding of VPP, and its strategy is to make the bidding curve with the maximum profit as the goal [56]. For Cooperative game that participates in the electricity market as a whole, the profit distribution can be based on the Cooperative game theory of the Shapley value method to create a new way to maximise the profit distribution of internal resources [57]. Taking the cooperative operation of wind power generation and electric vehicles as an example, the profit distribution problem between wind power suppliers and EV aggregators in the Cooperative game can be solved by introducing the bidding deviation punishment mechanism and designing the profit distribution method according to the uncertainty factors of wind power suppliers. They are making full use of the Shapley value method to solve the uncertainty factors of wind power suppliers.

4 | BLOCKCHAIN TECHNOLOGY IS APPLIED TO THE FUNCTION DESIGN OF P2P TRANSACTION OF DERs

This section presents the key technology of blockchain for DER P2P transactions from three aspects, that is, the service system, the aggregate system, and the terminal. We have mapped different blockchain functions (contract functions, traceability functions, inter-blockchain information sharing functions, security management functions, and game functions) to different VPP functions. Table 2 shows the procedure in detail:

5 | CONCLUSIONS

This paper discusses the current challenges of distributed energy transactions within VPP. The application of consensus algorithms, smart contracts, inter-blockchain technology,

TABLE 2 Virtual power plant (VPP) distributed energy resource P2P transaction function

System function		VPP distributed energy resource P2P transaction		
		Service system	Aggregate system	Terminal
User management function	User registration	A(M)B(O)C(O)D(M)E(O)	A(M)B(M)C(M)D(M)E(O)	A(M)B(−)C(O)D(M)E(O)
	Permissions	A(M)B(O)C(−)D(M)E(O)	A(M)B(O)C(O)D(M)E(O)	A(M)B(−)C(O)D(M)E(−)
	Information query	A(M)B(M)C(M)D(M)E(−)	A(M)B(M)C(M)D(M)E(−)	A(M)B(M)C(M)D(M)E(−)
Project management function	Project build	A(O)B(O)C(−)D(M)E(−)	A(O)B(O)C(O)D(M)E(O)	A(O)B(−)C(O)D(M)E(−)
	Project released	A(O)B(O)C(M)D(M)E(O)	A(O)B(O)C(O)D(M)E(−)	A(O)B(−)C(O)D(M)E(O)
	Project update	A(O)B(O)C(M)D(M)E(O)	A(O)B(M)C(O)D(M)E(−)	A(O)B(−)C(O)D(M)E(O)
	Delete	A(O)B(O)C(M)D(M)E(−)	A(O)B(−)C(M)D(M)E(−)	A(O)B(−)C(O)D(M)E(−)
Resource management function	Parameter maintenance	A(M)B(M)C(−)D(M)E(−)	A(M)B(M)C(−)D(M)E(O)	A(M)B(O)C(−)D(M)E(−)
	Acquisition control	A(O)B(M)C(O)D(M)E(−)	A(M)B(M)C(O)D(M)E(O)	A(O)B(−)C(M)D(M)E(O)
Event management function	Event notification	A(M)B(O)C(M)D(M)E(O)	A(M)B(M)C(O)D(M)E(−)	A(−)B(−)C(O)D(−)E(O)
	Regulatory order issuing	A(M)B(M)C(M)D(M)E(O)	A(O)B(M)C(O)D(M)E(O)	A(−)B(O)C(M)D(−)E(O)
	Load control	A(M)B(M)C(O)D(M)E(O)	A(M)B(O)C(O)D(M)E(−)	A(O)B(−)C(−)D(O)E(−)
Implement effect management function		A(M)B(M)C(O)D(M)E(O)	A(M)B(M)C(O)D(M)E(O)	A(M)B(M)C(O)D(M)E(O)
Other features	Security management function	A(M)B(M)C(M)D(M)E(O)	A(M)B(O)C(M)D(M)E(O)	A(−)B(O)C(−)D(M)E(O)
	Automatic execution function	A(M)B(−)C(O)D(M)E(−)	A(O)B(−)C(O)D(M)E(−)	A(M)B(O)C(O)D(O)E(O)
	Manual intervention management function	A(O)B(M)C(O)D(M)E(−)	A(O)B(O)C(O)D(M)E(−)	A(O)B(O)C(−)D(M)E(−)

Abbreviations: A, contract functions; B, traceability functions; C, inter-blockchain information sharing functions; D, security management functions; E, game functions; 'M', indicates a mandatory function; 'O', indicates an optional function; '—', indicates that this function is unavailable.

and game theory are analysed. In addition, the DER P2P transaction function is designed. This system function design provides a theoretical research foundation for the implementation of blockchain technology for DER P2P transaction systems. In the future, we will implement the system based on the system functions to provide a reliable and convenient trading environment for DER P2P transactions. At present, China is vigorously promoting distributed power generation. The application of blockchain technology to DER transactions within VPP can promote renewable energy accommodation and clean power generation. We hope that the research study in this article will have particular reference significance for the development of related applications.

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CONFLICT OF INTEREST

We do not have any conflict of interest to disclose.

PERMISSION TO REPRODUCE MATERIALS FROM OTHER SOURCES

None.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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