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Energy Transaction for Multi-Microgrids and Internal Microgrid Based on Blockchain

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ABSTRACT With the decreasing reserves of fossil energy and the increasing capacity of renewable energy generation, the scale of microgrid based on distributed generations is expanding. However, more operation data and transaction information of microgrids will also bring several problems: the sufficient capacity of the server in the central management needed, the crises of trust among members, the transparency of transaction information and the confidentiality of data storage. In this paper, blockchain technology is used to deal with these problems as distributed data storage technology. A double-layer framework of energy transactions based on blockchain in multi-microgrids is proposed to provide decentralized trading, information transparency and mutual trust system of each node in the trading market. The central node within the microgrid collects the demand information of the trading market in lower layer and sends them to the trading market of multi-microgrids in higher layer to seek the energy transaction. The continuous double auction mechanism is used in the trading market to guarantee free and fair transactions among nodes. The proposed transaction framework effectively reduces the transaction volume with the main grid which improves energy utilization. Comprehensive simulation results are presented to prove the feasibility of the proposed transaction framework.

INDEX TERMS Renewable energy generation, multi-microgrids, blockchain, decentralized, energy transaction.

I. INTRODUCTION

In recent years, microgrids (MGs) have become a research hotspot in the energy field. At present, there are more than 400 microgrid demonstration projects in the world under planning, constructed and put into use [1]. The characteristic of microgrid with flexible and efficient of DG units makes renewable energy which mainly includes Photovoltaic generation (PV) and Wind Turbine (WT) accessible on a large scale. Many studies have focused their research on microgrid operation control and energy management strategies. For example, a control technology of the distributed stabilized generator was used to control the voltage of the microgrid in [2]. In [3], the protection algorithm based on dynamic state estimation was proposed to minimizes the output oscillation during system disturbance. In [4], a distributed multi-period and multi-energy operation model was presented, which makes the electric, thermal and gas network synergistic and improves the economics of the system. At the same time, because of the flexible composition of the microgrids, the energy trading in microgrids has become an emerging power market in the presence of multiple nodes with different owners in the microgrid. Therefore, many accurate prediction technologies for renewable resource is studied to ensure a reliable environment of electricity transactions [5]–[7]. In [6], machine learning was used to predict solar power intensity. And the deep belief network for wind speed prediction was introduced and customized in [7]. In summary, these above

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studies have provided guarantees for the feasibility of energy trading in microgrids. The market participation of the microgrid includes three modes: power bank model, bilateral transaction model, and hybrid model [8]. However, due to the distributed structure of the microgrid, the electricity market in the microgrid also needs to have sufficient transparency, freedom and fairness.

Blockchain is a decentralized electronic accounting system proposed by Satoshi Nakamoto in 2008 [9]. However, the underlying technology used by the blockchain is not brand-new, but a combination of some known, such as proof of work mechanism, peer-to-peer (P2P) network, distributed network, cryptography and others [10]. The application of blockchain technology in the trading market is mainly divided into three stages as the blockchain 1.0 era with the birth of Bitcoin [11] and the 2.0 era with smart contracts [12]. And finally, with the more development of blockchain technology, it has entered the third stage nowadays. And the Brooklyn microgrid in the United States is the first typical case of applying blockchain technology in the world [13].

Therefore, the research of microgrid energy trading based on blockchain technology is concerned by many researchers [13]–[27]. In [13], a pricing system similar to the wholesale market was proposed in which the quotation is decided by sellers and buyers. Energy blockchain was applied to microgrids in [14], and a real-time attribution of power losses to each transaction by defining some suitable indices. In [15], a distributed power trading system for producers in Active Distribution Networks (ADN) was proposed. It solves the problem of determining the price of energy trading and the safe settlement of energy trading transactions separately. The auction mechanism for microgrid energy transactions was modified to combining differentiated privacy with microgrid auctions based on decentralized blockchain in [16], and the DEAL algorithm is developed to protect the auction results to maximize the revenue of microgrid. In [17], a secure localized P2P power trading system was developed, which establishes a consortium blockchain technology to review and verify transaction records between Plug-in Hybrid Electric Vehicles (PHEVs). And an iterative double auction mechanism was proposed to maximize social welfare. In [18], the blockchain technology and the multi-signature method was used to ensure the privacy and security of decentralized electricity market without relying on any third-party organization. However, the electricity is just taken as a general commodity in this paper, which leads to price scheme and compensation mechanism for breach of contract not being flexible enough to deal with the complex market environment of the microgrid. A peer-to-peer energy market architecture was proposed in [19], which the smart contract technology is used to guarantee the automatic, safe and reliable operation of the microgrid. The Lyapunov optimization method is applied to determine the amount of shared energy in [20]. However, it only considers the amount of shared energy without determining the price. In [21], a consensus principle and an incentive mechanism based on blockchain were designed by analyzing different autonomous strategies of nodes. And in [22], a consensus-based distributed energy management algorithm using local information is designed by analyzing attack resistance from the perspective of data integrity. Although the application of blockchain technology in the energy Internet is still flawed [23], it can provide more possibilities for establishing a decentralized electricity market framework. A cyber-enhanced transactive microgrid model using blockchain technology with optimized participants' permission protocol was proposed in [24] to improve transaction speed and greater convenience. The possibility of using the blockchain technology for load and generation aggregation in a new distributed Demand Response (DR) service and customer remuneration system is proved in [25]. In [26], a consortium blockchain trading model to support P2P energy trading using proof-of-stake protocol is designed, and a type of crypto-currency named 'elecoin' is allowed to circulate in the market. And in [27], a secured architecture for the optimal operation of smart hybrid AC-DC microgrids with a proper DAG-based data transaction framework is proposed, in which a stochastic approach based on Modification Teacher Learning Algorithm (MTLA) and Point Estimate Method (PEM) is used to solve the optimal power scheduling.

So far, no research has been done to design an electricity market transaction framework for the multi-microgrids (MMGs) based on blockchain considering both the transaction internal microgrid and among microgrids. Therefore, in order to fill the research gap in this area, this paper proposed a double-layer framework of energy transactions for multi-microgrids and internal microgrid based on blockchain. The main contributions of this paper are summarized as follows:

1) By analyzing the key technical points of the blockchain and the characteristics of the electricity market in microgrids, the applicability and high degree of fit of the blockchain in the microgrid transaction are summarized.
2) A transaction method using continuous double auction mechanism is proposed to guarantee the freedom and fairness of transactions among nodes. The blockchain technology is applied to realize the decentralization and transparency of transactions.
3) A double-layer energy trading framework based on blockchain is designed including physical and information architecture, which realizes the transfer of transaction information between the trading markets within the microgrid and the multi-microgrids system.
4) Comprehensive simulation scenarios are designed to verify the feasibility of the proposed trading framework. The results show that the proposed framework effectively increases the transaction behavior between nodes, and electricity is preferentially traded between nodes, which the transaction volume with the main grid is reduced.

This paper is organized as follows. Section II gives the description of the key technology of blockchain and the suitability analysis. Section III shows the energy transaction framework for multi-microgrids and internal microgrid. Section IV analyzes the results of the simulation scenarios. Finally, conclusion is presented in Section V.

II. BLOCKCHAIN INTRODUCTION AND FIT ANALYSIS

This section describes the operation mechanism and principle of blockchain. The operating characteristics of the microgrid electricity market and the blockchain are compared, and the applicability of the blockchain in microgrids is analyzed.

A. OPERATION MECHANISM OF BLOCKCHAIN

Bookkeeping is regard as the core of the transaction because the ledger is the most basic data structure in the transaction. With the transaction method based on blockchain, the ledger is stored in every node. Each node has the right to record the ledger by paying the corresponding price. The node who record the ledger successfully will be rewarded by the system according to the rules, which not only effectively prevents malicious nodes from attacking the blockchain, but also increases the enthusiasm of each node for trading behavior.

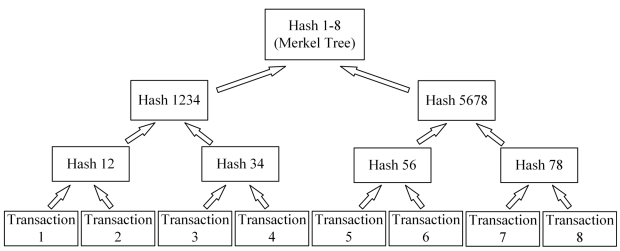

FIGURE 1. The structure of the Merkel tree.

In order to further ensure the reliability of the transaction, the Merkel tree data structure which called the hash tree is used in blockchain. The structure of the hash tree was shown in Fig. 1. As shown in Fig. 1, the hash tree is divided into leaf nodes and non-leaf nodes. The hash value obtained by encrypting a transaction information between nodes through the hash algorithm will be stored in a leaf node. And the leaf nodes will be concatenated according to the adjacent transactions. Then the waiting data is hashed to get the upper level node, which is repeated continuously until a root node is obtained. And the root data of the hash tree will be stored in the block headers with the hash value of the parent block and time stamp, etc. Therefore, if any data in the transaction ledger is artificially changed, it will cause the root data of the hash tree to change. This mechanism can be used to verify whether the data has been tampered. Moreover, all blocks are connected into a chain according to the hash pointer in the block header to be a complete block chain [28], [29]. In summary, the operation mechanism of blockchain is shown in Fig. 2. And the verification items of the transaction information are listed in Table 1.

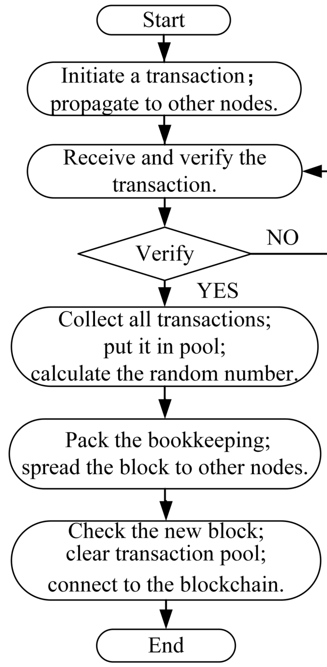

FIGURE 2. The blockchain operation mechanism.

TABLE 1. Project Inspection.

Number	Project
1	Check if it is double spending
2	Confirm that the input amount cannot be lower than the output amount
3	Check whether the return value of the script is TRUE
4	Check if this transaction is received by this node, the node will put the verified transaction into its transaction pool and forward the transaction

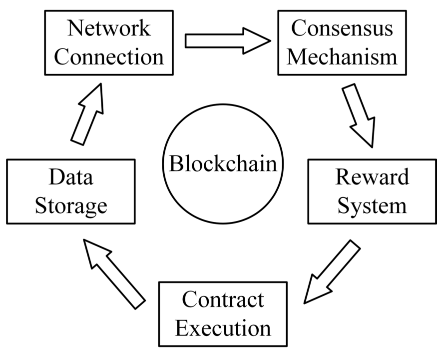

FIGURE 3. The structure of Blockchain.

B. THE KEY TECHNOLOGY OF BLOCKCHAIN

As shown in the Fig. 3, the structure of the blockchain has five modules. For data storage module, the hash algorithm is applied as an encryption algorithm that can encrypt the transaction information in blockchain as characters which are binary. And the length of these binary characters is fixed no matter how long the original content is before the encryption.

Moreover, the hash algorithm is an asymmetric encryption mechanism. It only has the encryption process, which means there is no possibility to get the original text by reversing the encrypted binary characters. This encryption mechanism can prevent the information in the blockchain from being stolen by malicious nodes.

The encryption process of hash algorithm is random, that means if the information before encryption is slightly changed, the result after encryption will be hugely different. The randomness of the hash algorithm can prevent the information in the blockchain from being easily cracked. More importantly, the time consumed by hash function with different input information is almost the same. It makes the operation speed of each node in the block almost the same, which ensures the fairness of the transaction.

Moreover, with the development of big data technology, third-party central institutions have mastered massive data. And the credibility and authority of these third parties will become higher, which will gradually change the status of third-party central institutions. And they can deduce the transaction rules implied in massive transaction data, which can create new value for third-party central institutions [30]. Therefore, a decentralized transaction mechanism is necessary to applied to solve the fairness problem caused by the intervention of third parties.

Therefore, blockchain technology has a consensus algorithm module. The consensus mechanism is used to make the consistency of the content recorded by each node in the blockchain when there is no intermediate institution [31]. And it can establish an internal consensus mechanism that can enforce mutual trust among nodes, so that nodes can operate stably in the deblocking chain without the third-party organization [32].

TABLE 2. Fit Analysis Between Blockchain and the Trading Market in Microgrids.

Problems of electricity market of microgrids	Solutions by blockchain
Member decentralization	P2P network
Information security and privacy	Hash encryption algorithm
Transaction transparency	Ledger mechanism and Consensus algorithm
Cooperation trust	Smart contract and Compensation for breach

On the other hand, due to the features of decentralization, self-management, and marketization, the microgrid and multi-microgrids architecture show significant advantages in the local consumption of renewable energy generation [33], [34]. In summary, as comparison shown in Table 2, the blockchain technology is fully met about requirements of the characteristics and needs of the electricity market of microgrids. In other words, the transaction framework of microgrids based on blockchain has strong feasibility.

III. MICROGRID TRANSACTION FRAMEWORK BASED ON BLOCKCHAIN

In this section, the framework of the transaction model based on blockchain in microgrid and multi-microgrids system is described. And a double-layer method of energy transaction based on continuous double auction is proposed.

A. THE OVERALL FRAMEWORK OF THE TRANSACTION MODEL

The framework of the transaction model in internal microgrid and multi-microgrids system is shown in Fig. 4. The alliance chain is used for the market framework proposed in this paper. It means that information can be transferred among nodes through P2P network. The node in the trading market with surplus energy is considered as a producer, and considered as a consumer conversely. Before reaching the specified time, each node who wants to participate in the trading market must broadcast its predicted demand of transaction and its expected price for the next period. However, not all nodes can participate in bookkeeping, because they are regarded as general nodes in blockchain [6]. The only nodes that can participate in accounting among them are the main power grid and the central trading platform of each microgrid.

And in reality, the generation and consumption predictions of microgrids cannot be 100% accurate. Therefore, the main grid should be connected as an auxiliary transaction point to participate in the microgrid market transaction for regulation of power and elimination of power error, which should be included in the microgrid market transaction framework.

Therefore, as shown in Fig. 4, the framework is divided into two layers. The physical layer contains the entity such as the users, dispatching agency and grid enterprise. The virtual layer contains the information system, the dispatching system and the trading system. This framework ensures that the nodes can freely conduct transactions within a day to meet the power balance of the system. After the transaction among nodes, if the power is still surplus or lack, nodes can also trade with the main network to ensure the stability of the system and the normal power consumption of users.

Due to the cost of electricity transportation, the power generation of the DG units and the power consumption of the load must be prioritized to balance, that is, the electricity transactions in the trading market within the microgrid is regarded as the lower layer of the transaction model.

In addition, in order to pursue higher economy, microgrids in a same MMGs system are more prefer to create a side chain to each other. The MMGs includes several regional microgrids and also connected with main grid. Each microgrid can be regarded as a node. Energy transactions can be conducted among these microgrids, and each microgrid can also conduct transactions with main grid if there is remaining energy. Therefore, the energy transaction among microgrids is regarded as the higher layer of the transaction model.

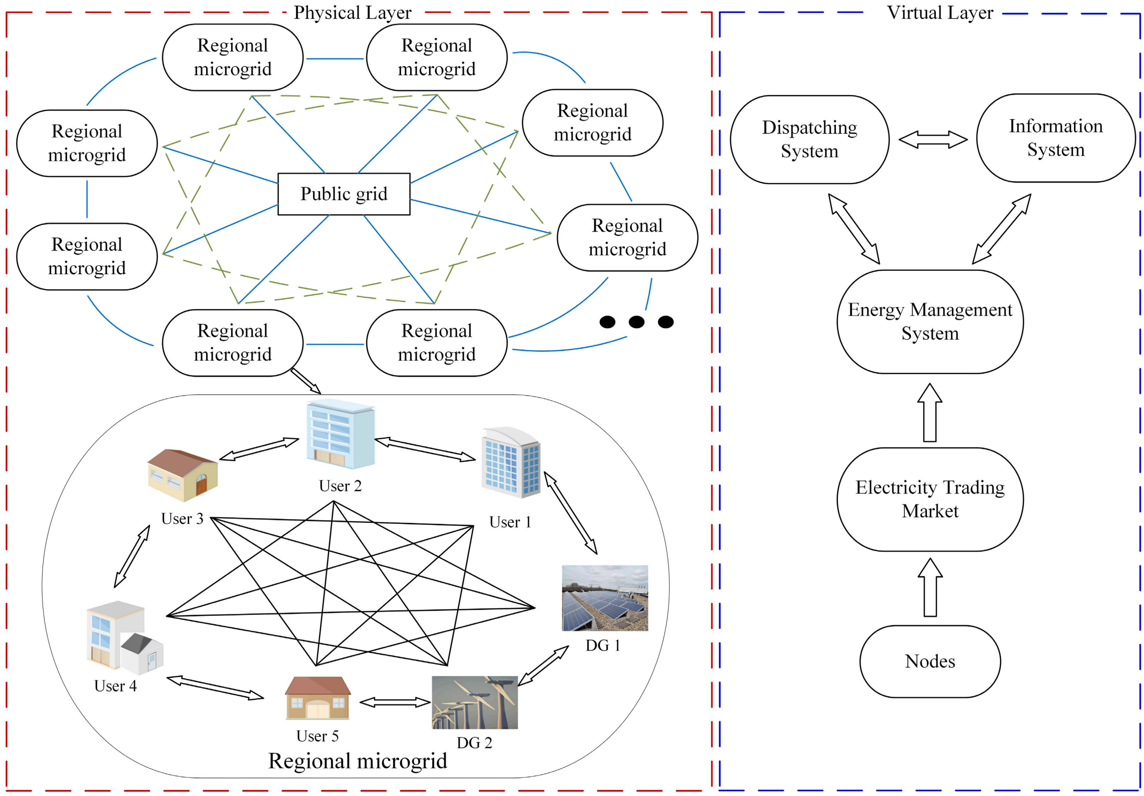

FIGURE 4. The framework of transaction model in MMGs and internal microgrid.

Moreover, the transaction among nodes will be conducted according to the smart contract in the blockchain. At the end of trading, the central node will package all the information into a block which connects to the blockchain. Therefore, the transaction information of internal microgrid, the transaction information among microgrids, and the transaction information between the microgrid and the main grid will all be contained in a block [35]. The network model of the transaction is shown in Fig. 5.

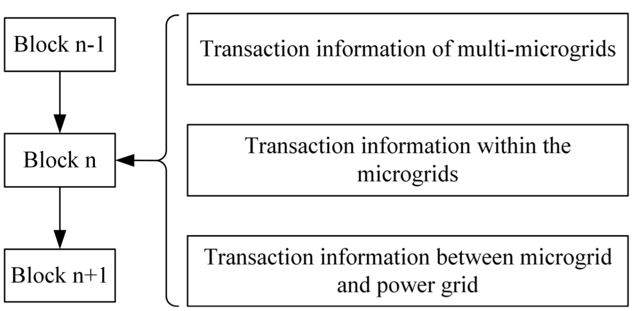

FIGURE 5. The network model of transaction.

B. POWER TRADING BASED ON CONTINUOUS DOUBLE AUCTION

Transactions between nodes will be implemented on the principle of price priority. Therefore, continuous double auction is adopted as the method of power trading. The double-auction transaction mechanism refers to a transaction form with multiple sellers and multiple buyers. Buyers and sellers can submit quoted price at any time during the transaction cycle. If the buyer matches the seller, the transaction can be concluded [36], [37]. The buyer's price is sorted from high to low, and the seller's price is sorted from low to high. In the case of the same price, it is sorted according to the time of submitting the quoted price.

In the first round of bidding, there is no reference information of the dealing price, the node will use its own reserve price as the bid:

$$P_{bid} = P_{re} \tag{1}$$

where P_{bid} indicates the bidding price. And P_{re} is the reserve price of a node:

$$P_{gb} < P_{re} < P_{gs} \tag{2}$$

where P_{gb} is the sale price to main grid and P_{gs} is the purchase price.

During the transaction, the consumers and producers are all want to make more profits for themselves. Therefore, the quotation of each round will be constantly adjusted. In the next auction round, the quotation method of nodes is as follows:

$$\begin{cases} P_{bid}(k) = P_{bid}(k-1) + (1 + (\sigma - 1)P_{re}) \\ \quad\quad node \in consumer \\ P_{bid}(k) = P_{bid}(k-1) + (\sigma + (1-\sigma)(1-P_{re})) \\ \quad\quad node \in producer \end{cases} \tag{3}$$

where k represents the auction round. The bidding price of the next round will be adjusted according to the previous round of quotation and transaction result. σ indicates the attitude towards bidding price for node. And it needs to meet:

$$-1 \le \sigma \le 1 \tag{4}$$

The larger σ means the more aggressive bidding strategy is made by node, and the smaller means more negative. Moreover, $\sigma = 0$ means the nodes are conservative. As more market information is obtained, the attitude of node towards bidding will also change:

$$\sigma = \sigma + \lambda \cdot \alpha \tag{5}$$

where λ is an integer variable that indicates whether satisfied with its bid price compared with the dealing price:

$$\lambda = \begin{cases} 1 \\ -1 \end{cases} \tag{6}$$

For consumers, if $P_{bid} > P_{deal}(k-1)$, it means that the expectation of purchase price of power is over higher, where $P_{deal}(k-1)$ represents the dealing price of the last round of transaction in market. Therefore, the consumer tends to lower its expectation of purchase price which means $\lambda = -1$. On the other hand, if $P_{bid} < P_{deal}(k-1)$, $\lambda = 1$. And the opposite is true for producer. Moreover, $\alpha \in [0, 1]$ indicates the adjustment coefficient. Its size selection is related to the historical transaction price and the operation strategy of the node. The larger α indicates that the node is more actively to change its bidding price for anticipation of a deal.

After receiving the information broadcast of the entire network, the nodes will choose the dealing partners. If there is a cross between the lowest price from producer and the highest price from consumer. They will make a deal. The dealing price is the average of quotations from the two:

$$P_{deal} = \frac{P_{bid,con} + P_{bid,pro}}{2} \tag{7}$$

where P_{deal} is the dealing price in the current round of auction. $P_{bid,con}$ and $P_{bid,pro}$ are the bidding price of parties of the deal.

It is worth noting that electricity is not sold in one go. As we can see in (3), compared with one-time transactions, nodes are more willing to wait for the next round of quotations to obtain greater benefits. Therefore, the amount of electricity per transaction is expressed as follows:

$$W_{deal} = \beta W_{bid} \tag{8}$$

where β is a constant coefficient with $0 < \beta < 1$. W_{deal} indicates the final transaction amount of power. And W_{bid} is the bid amount of power, which is determined by the supply and demand relationship of the two parties to the deal:

$$W_{bid} = \begin{cases} W_{bid,con} & \text{if } W_{bid,con} < W_{bid,pro} \\ W_{bid,pro} & \text{if } W_{bid,con} > W_{bid,pro} \end{cases} \tag{9}$$

When the transaction is completed, the buying and selling nodes will exit the market to wait for the next round of bidding. The remaining nodes in the market will continue to seek transactions until all nodes have no willingness to trade or the next auction is open. And before the arrival of the next auction round, the node will optimize its quoted price and bidding strategy as shown in (3) and (5).

C. ENERGY TRANSACTION FOR INTERNAL MG AND MMGS BASED ON BLOCKCHAIN

The flowchart of the entire transaction model is shown in Fig. 6. Energy transaction based on blockchain proposed in this paper is divided into two layers. On the lower layer, each node in a microgrid broadcasts the predicted amount of electricity generation, electricity consumption, and expected transaction price to others. Within the specified time, each microgrid completes internal transaction base on continuous double auction through smart contracts in the blockchain. At this moment, the power generation and the consumption among nodes in microgrid may be imbalanced. Therefore, on the higher layer, each central trading platform of the microgrid will count its own surplus and then broadcast the entire MMGs with the expected transaction price.

Then the electricity transactions among microgrids will be conducted in the trading market of MMGs system. And finally, if the power deviation is still existing, microgrids will make a deal with the main grid. Transactions among microgrids and internal microgrid are based on the same blockchain. And the specific transaction process is summarized in nine steps as follows:

Step 1: The DG units and users in the microgrid predict their own power generation and consumption for the next period based on the historical data and current status information in the smart meter.

Step 2: Each node announces its transaction information to the others based blockchain through the P2P network.

Step 3: Each node queries the transaction information and the remaining balance based on the visual interface provided by the blockchain application layer. Then each node gives its own bidding price and broadcasts them to the entire network of microgrid.

Step 4: Transactions of the internal microgrid are conducted in the trading market based on the continuous double auction, and the deals are recorded in the blockchain.

Step 5: The center node of each microgrid counts its own power demand according to the transaction records in the blockchain.

Step 6: Transactions among microgrids in a MMGs system are conducted through the trading market in blockchain like Step4. And the deals are also recorded.

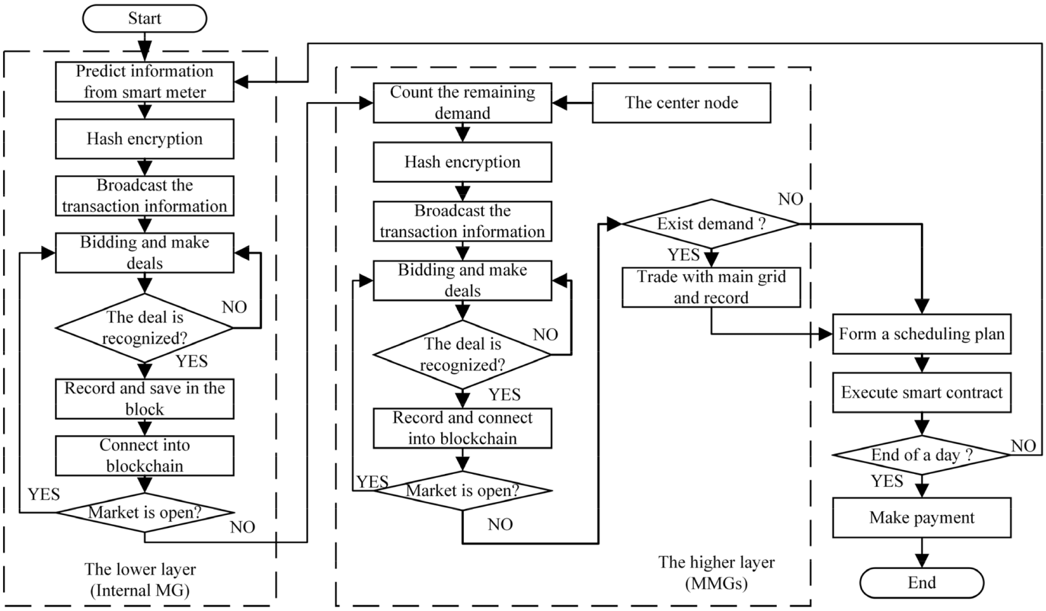

FIGURE 6. The flowchart of the transaction model based on blockchain.

Step 7: If the demand is still existing after the trading market closed, microgrids will trade with the main grid and record the transaction in the blockchain.

Step 8: A scheduling plan will be formed, and recorded in the blockchain with the form of a smart contract.

Step 9: When the trigger conditions of the smart contract are satisfied, the payment will be made through the blockchain.

IV. SIMULATION RESULTS AND DISCUSSION

The electric energy trading method proposed in this paper is applied in a MMGs system with eight independent microgrids which the framework is shown as Fig. 4. And all simulations were run in MATLAB.

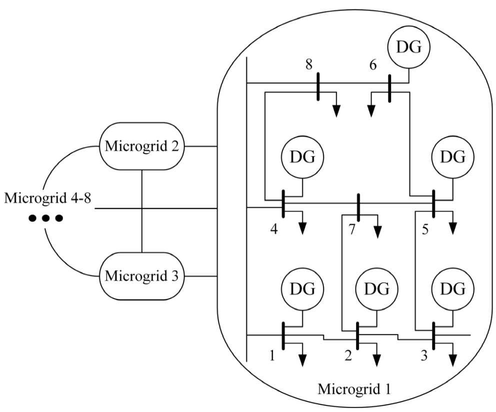

FIGURE 7. The topology of 8 nodes in a microgrid.

A. TRANSACTION WITHIN THE MICROGRID

Eight nodes of users and DGs were assumed in an independent microgrid. And the topology of this microgrid is shown in Fig. 7. The transaction information of each node in a certain period of a day is shown in Table 3 and Table 4.

TABLE 3. Transaction Information of Users.

Users	1	2	3	4	5	6	7	8
Forecast demand (kWh)	150	80	100	210	110	150	260	100
Reserve price (￥/kWh)	1.5	1.4	1.3	1.3	1.7	1.5	1.4	1.5

TABLE 4. Transaction Information of DGs.

DGs	1	2	3	4	5	6
Forecast supply(kWh)	200	160	50	100	170	110
Reserve price (￥/ kWh)	0.6	0.45	0.4	0.5	0.65	0.8

As shown in Fig. 7, there are eight users and six DG units in this microgrid, and the whole microgrid is connected to other microgrids network. All nodes can freely buy and sell electrical energy. And every transaction and bid can be queried on the visual blockchain application. The results of the transaction are shown in Fig. 8, Fig. 9 and Fig. 10.

Statistics on the number of transactions among nodes in a time period are shown in Fig. 10. Multiple transactions were occurred among users and DG units based on electricity prices. Many transactions were successfully completed by parties of the transaction, which in order to form a blockchain with 31 blocks. And due to the time limit with broadcasting and recording in blockchain, the number of transaction rounds was six. Among them, user 1 and DG 2, user 3 and DG 8 reached the most transactions. However,

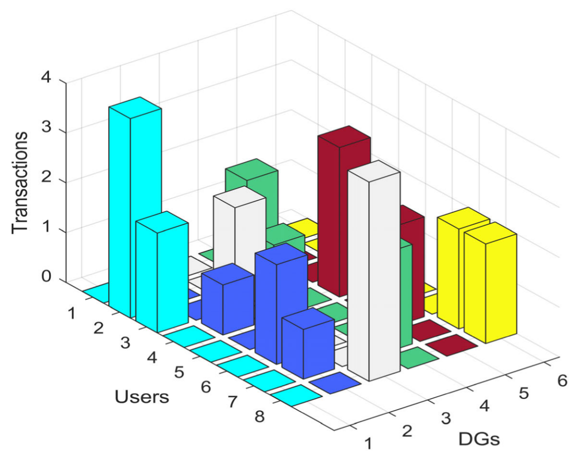

FIGURE 8. **The number of transactions among nodes.**

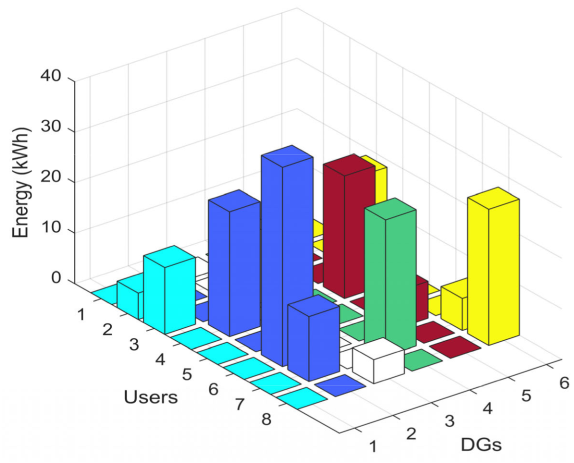

FIGURE 9. **The amount of power trade in transactions among nodes.**

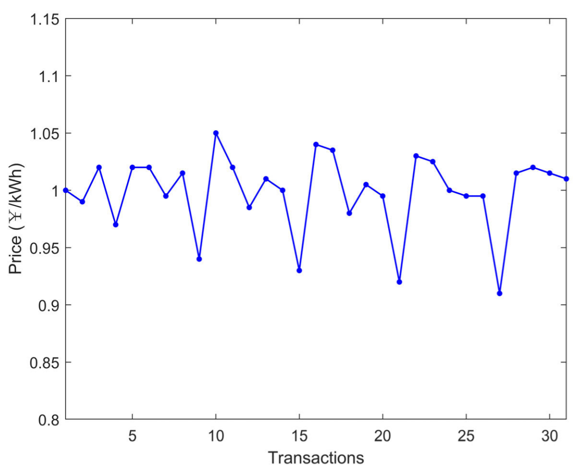

FIGURE 10. **The dealing price of each transactions.**

as the total electricity statistics of the transaction shown in Fig. 9, the transaction volume reached among these nodes is very small. This is because the reserve price of their transaction is too low or too high, so that the bid price cannot be quickly revised to suit the market. Therefore, the transaction among them only occurs at the end of each round of auction.

Moreover, the dealing price of each deal is shown in Fig. 10. It should be clear that, due to the continuous auction mechanism we described in Section III-B, there will be multiple rounds of bidding in a time period, and each round of quotation will generate multiple transactions. Therefore, the abscissa indicates the order of deals recorded in the blockchain. Each point represents the real dealing price per kWh finally recorded in each blockchain. Due to the time limit of using blockchain, the bidding strategy of each node may appear more aggressive, which increases the enthusiasm of transactions and reduces the time required for transaction negotiation. However, it is obvious that the price always fluctuates within the acceptable range of the market. The biggest change occurs at the junction of each round of transactions, which is the result of starting a new round of bidding. And with the adaptation to market prices, this mutation is gradually shortening.

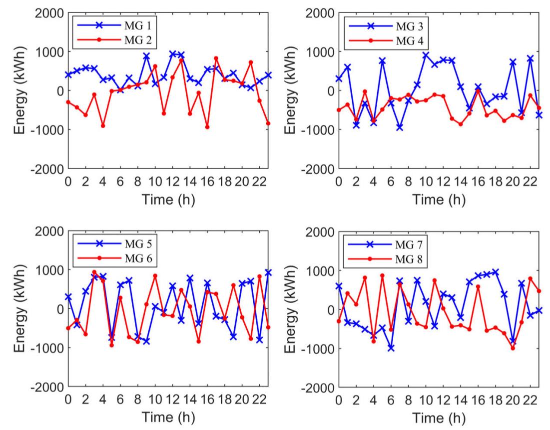

FIGURE 11. **The demand of each microgrid within a day.**

B. TRANSACTION WITHIN THE MULTI-MICROGRIDS SYSTEM

Eight microgrids were considered to compose a MMGs system. The trading market is opened at an interval of one hour, and each market conducts ten rounds of auction transactions. The demand of each microgrid within a day are shown in Fig. 11. When the demand is greater than zero, it means that the microgrid hopes to sell the surplus power, when the demand is less than zero, it means that the microgrid hopes to purchase the lack of power.

As shown in Fig. 11, the demand of each microgrid shows great volatility and uncertainty in a day. If the traditional transaction center is used to replace the blockchain, then with the increase of MMGs members, a large amount of and complex data will undoubtedly bring storage pressure on the central server. And in addition, encrypted by the blockchain makes it impossible for members to tamper with transaction data, which ensures the fairness of each transaction. Moreover, the transaction information of each MG is shown in Table 5.

TABLE 5. Transaction Information of MGs.

MG	1	2	3	4	5	6	7	8
Reserve price (buy)/(¥/kWh)	0.5	0.65	0.6	0.55	0.8	0.7	0.6	0.75
Reserve price (sell)/(¥/kWh)	1.2	1.4	1.4	1.3	1.7	1.5	1.6	1.5

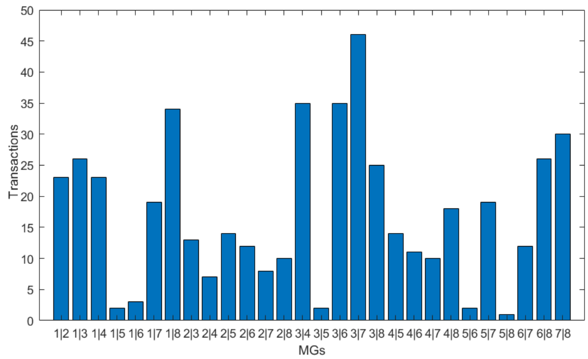

FIGURE 12. The number of transactions among microgrids.

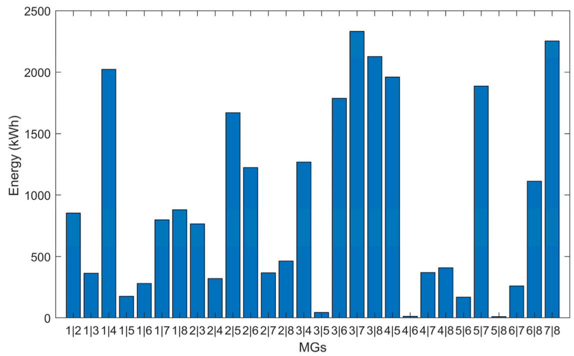

FIGURE 13. The amount of power traded in transactions among microgrids.

The trading statistics for one day are shown in Fig. 12 and Fig. 13. Fig. 12 shows the statistics of the number of transaction interactions among microgrids, and Fig. 13 shows the amount of electricity traded in a day. And in order to better represent the interaction between microgrids, we use '$X|Y$' to represent the interaction between MG X and MG Y as the abscissa shown in Fig. 12 and Fig. 13.

As shown in Fig. 11, the forecasted power generation of MG 1 is in a surplus state in the whole day, so MG 1 will basically participate as a seller in the trading market. On the contrary, MG 4 will participate as a buyer. And the others will determine their identity due to different situations of demand at different times. At the end of the day, as shown in Fig. 12, free choice transactions have been achieved among all microgrids. Since the blockchain is a chain connected from the block head to the end of another block, each transaction will be recorded in chronological order, ensuring that such a large amount of transaction information can be processed in an orderly manner.

And as analyzed in Section IV-A, the use of blockchain has achieved the same effect. Since the condition of each account in the blockchain is recognized by the vast majority of nodes and the result will be passed to everyone by the consensus mechanism, it is guaranteed that each transaction is in the interest of most nodes. However, due to the difference in individual expected prices and the different attitudes towards the progress of bidding, the connection between microgrids has shown a difference in strength. For MG 1, although multiple transactions were made with MG 2, MG 3, and MG 8 in one day, the total transaction volume was lower. However, due to the difference in individual expected prices and the different attitudes towards the progress of bidding, the connection between microgrids has shown a difference in strength. For MG 1, although multiple transactions were made with MG 2, MG 3, and MG 8 in one day, the total transaction volume was lower. However, there is the potential for long-term trading cooperation with MG 4 because of the large transaction volume. For MG 3, due to the large expected transaction volume at each hour, it is always actively seeking transactions with others in MMGs. The statistical results also show that the frequency and volume of transactions of MG 3 and almost everyone are relatively large; therefore, it can meet its internal supply and demand more economic relied on this energy transaction method. And for MG 5, because of its conservative bidding strategy, it has less interactive selectivity, and basically focuses on the connection between MG 4 and MG 7. The cooperation in the trading market among the three MGs is relatively close. If MG 5 can change its bidding attitude as a more aggressive one, it will get more trading options and benefits.

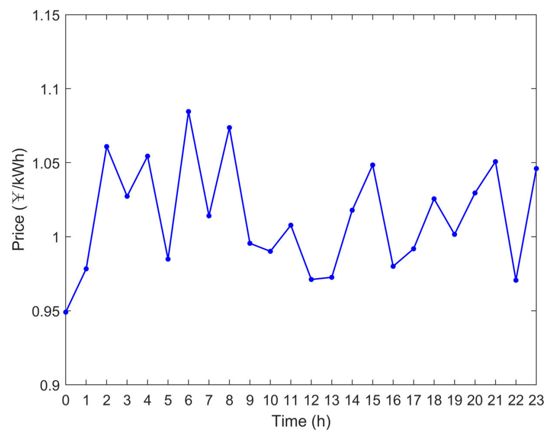

FIGURE 14. The average transaction price per hour.

Moreover, the average transaction price per hour is shown in Fig. 14. Each point represents the average of all actual dealing prices per kWh reached during the period at the end of an hour. Although the expected transaction price and the bidding strategy of each microgrid are different, the average transaction price per hour is mainly affected by the supply and demand relationship in the market. When the supply exceeds demand in the market, the buyer becomes the dominant player, and the average price will drop rapidly.

On the contrary, it becomes seller-led. Therefore, the average transaction price of the day will fluctuate indefinitely, but it is always limited to the acceptance range of each MG. This brings the possibility of more various trading strategies for balancing supply and demand within the microgrid. With learning for trading price in the past, MGs can also change its trading strategy in the MMGs trading market by optimizing its internal supply and demand balance, such as energy storage systems, to obtain greater economic efficiency.

V. CONCLUSION

In this paper, the architecture and operating mechanism of the blockchain are described in detail to prove the high degree fit between the microgrid power transactions and blockchain technology. And the impact of microgrid transactions from the perspective of blockchain technology is studied. The framework of the transaction model based on blockchain in microgrid and multi-microgrids system is described to improve the current mainstream microgrid trading methods in the power market. And a two-layer method of energy transaction based on continuous double auction is proposed, which expounds the physical transaction framework as well as the transaction process according to chronological order. Finally, the real-world data are employed in the simulation analysis which set up transaction scenarios of multi-microgrids and internal microgrid. Based on the comprehensive simulation, the proposed trading strategy can be proven that it is reasonable, feasible and economically efficient.

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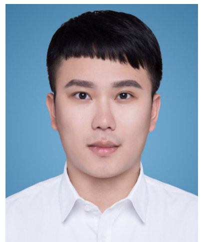

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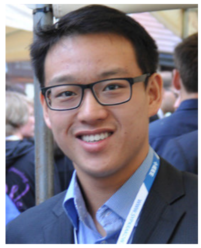

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