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Approach to Power Energy Transaction in Microgrid Based on Blockchain

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Abstract- With the growing maturity and penetration of distributed generation technology in microgrid, the participation of a large number of power prosumers brings new opportunities and challenges to microgrid power trading. A method of decentralized transaction of microgrid electric energy is suggested based on blockchain. Firstly, a method of power ownership and token exchange in microgrid based on blockchain system is proposed. In the blockchain system, prosumers and consumers trade power ownership and tokens, and multi-signature scripts are used to ensure the smooth settlement of transactions. Then, a method of matching microgrid power based on auction mechanism and a strategy of consumer bidding are proposed. Auction mechanism and valuation strategy are used to motivate consumers to bid rationally, to enhance the internal consumption of microgrid, and to maintain the balance between supply and demand within microgrid. The example shows that the method can conduct multilateral bidding transactions and effectively improve the self-consumption within the microgrid. Meanwhile it can ensure the economic benefits and the safe operation of the microgrid.

Keywords- *Blockchain, Auction Algorithms, Microgrid Power Trading, Multiple Signatures, Decentralized Trading*

I. Introduction

With the orderly advancement of power system reform, prosumers of distributed generation will be able to conduct electricity market transactions and participate in market competition [1, 2]. There will be a large number of prosumers trading in the electricity market in the microgrid. However, the electricity trading between prosumers and consumers has the characteristics of large orders, small scale and decentralization. There is no suitable trading platform between the two sides, and the transaction cannot be completed directly. Therefore, how to design a safe, efficient, symmetrical and transparent method of micro-grid power trading to achieve efficient allocation of power resources is the focus of micro-grid reform [3].

In order to ensure the safe and effective operation of microgrid, the idea of decentralization can be introduced into microgrid transactions, and blockchain technology is applied in microgrid transactions [4, 5]. Information transparency, decentralization and other characteristics are the core advantages of block chain technology, which ensures that both parties can trust each other in the absence of a third-party trust agency, thereby reducing the cost of maintaining trust [6, 7].

At present, the introduction of blockchain technology in the field of microgrid power trading is in its initial stage [8-10]. The relationship between different market mechanisms and consumer bidding strategies in microgrid power market is studied in [11]. Reference [12]proposes a distributed security checking algorithm, which uses a weak centralization management method for power trading. However, this method still relies on third-party trust agencies and does not complete the real decentralization. Reference [13] summarizes the application of blockchains in energy Internet from various dimensions, and discusses the role of blockchains in various scenarios of energy Internet application from various perspectives. Reference [14] discusses the mechanism of power trading based on blockchain and multi-signature. The mechanism of multi-signature guarantees the rights and interests of both parties. However, this method does not design an effective market mechanism and lacks an appropriate user bidding strategy.

In this paper, a method of decentralized transaction of microgrid based on blockchain technology is proposed. Both sides of the transaction exchange tokens and power ownership information through blockchain system, which protects the privacy of both sides, ensures the information security, symmetry and transparency of the transaction, and guarantees the interests of both sides of the transaction. A matching method of microgrid power based on auction mechanism is designed, and a consumer bidding strategy based on power evaluation is proposed. The microgrid is controlled by economic factors to complete the decentralized transaction of microgrid power.

II. Overall Architecture

Microgrid electricity trading achieves the matching of electricity quantity and price by auction mechanism, and guarantees the smooth progress of transaction content through blockchain technology. The overall structure is shown in Fig.1.

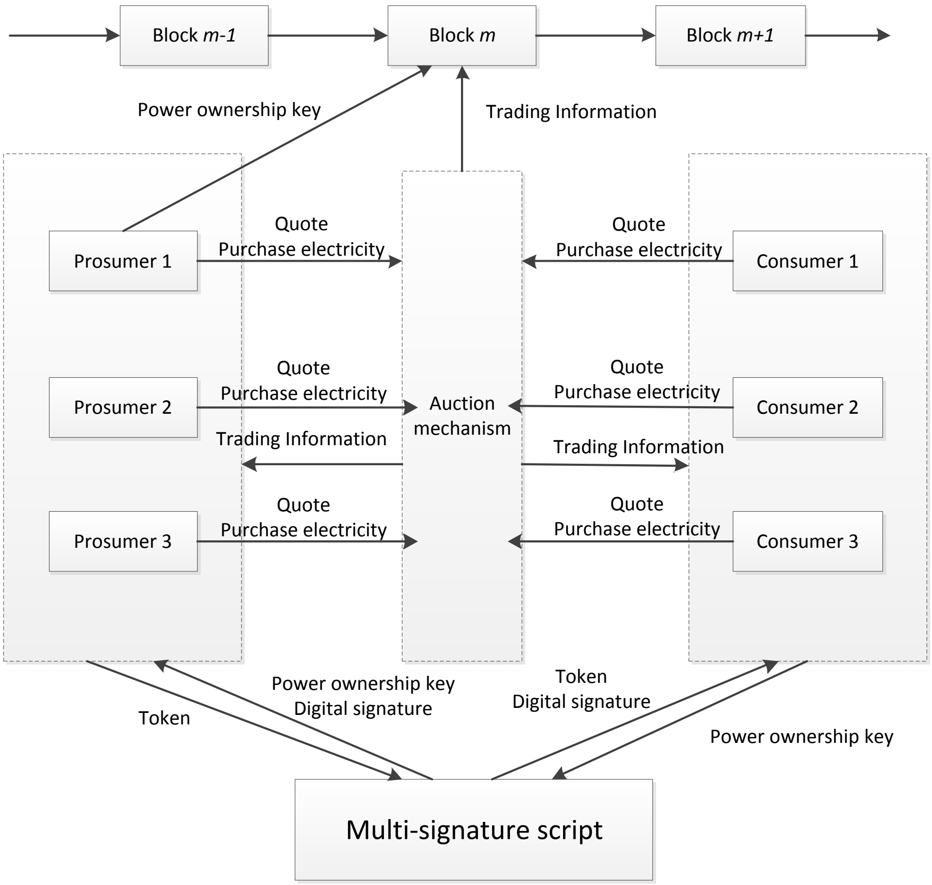

Figure 1. Overall framework of microgrid power trading

Blockchain information system collects bidding information from both sides of the transaction, completes automatic matching between prosumers and consumers through auction mechanism, calculates the set of consumers that each prosumer wins the auction, and broadcasts the successful bidding price of consumers' electricity. The multi-signature script in blockchain technology is used to ensure that the transaction goes smoothly. The prosumer and consumer sign the multi-signature transaction script after matching the power. The whole network is broadcast and authenticated by each node. The prosumer send the corresponding ownership key to the consumers who win the bidding through the blockchain. The consumer pays tokens to the prosumer through the blockchain.

A. *Maintaining the Integrity of the Specifications*

Assume that the structure of the transaction model T used below is represented by the following equation:

$$T = t - version || tInNumber || tIn || \\ tOutNumber || tOut || t - Time \tag{1}$$

Whereas tIn and tOut represent the input and output of this transaction, tInNumber and tOutNumber represent the quantity of input and output of this transaction. t – version is the version number of the transaction record and t – Time is the transaction authentication time. In microgrid power trading, suppose prosumer B spends money transferred to him by consumer A. A writes output script in tOut of transaction T_1, and indicates the number of tokens indicating that tokens are transferred to B. At the same time, B needs to write an input script in tIn of transaction T_2 to indicate that B wants to consume the tokens A pays B in T_1. Transaction T_2 will be broadcast throughout the network, and the node will verify the transaction T_2 according to the verification script information. When the input and output scripts are validated successfully, the node agrees that B can consume these tokens.

B. *Transaction script and multi-signature script*

In microgrid power trading, transaction script is the operation control language. In the P2SH script, sender A needs to send the redemption script (rScript) to receiver B, and then sender A hashes the redemption script (rScript) and generates the output script (pubScript). The formula is as follows:

$$rScriptHash = RIPEMD160(SHA256 \\ (rScript)) \tag{2}$$

Receiver generates input script (sigScript) containing signature. When Receiver B wants to use script assets, it needs to show input script. Blockchain node will compose validation script with input script (sigScript) and output script (pubScript). After validation, Receiver B obtains the right to use script assets. The structure of the P2SH script is as follows:

$$\begin{cases} sigScript :< sig > [sign]...[sign] < rScript > \\ pubScript\text{:} \quad OP\_HASH160 < rScriptHash > \\ \qquad\qquad OP\_EQUAL \end{cases} \tag{3}$$

Recipients can use rScript and signature to gain access to assets. When a transaction script uses a multi-signature script, it is expressed as:

$$\begin{aligned} rScript = OP\_m \ < pubKeyA >< pubKeyB > \\ < pubKeyC... > \ OP\_n \\ OP\_CHECKMULTISIG \end{aligned} \tag{4}$$

The implication of this multi-signature script is that the transaction is recognized only when there are at least m corresponding digital signatures in the n public keys contained in the script.

C. Anonymous message and digital signature

The main applications of asymmetric encryption technology in blockchain are anonymous information flow and digital signature. In the anonymous information flow scenario, the sender A of the message encrypts the information using the public key of the receiver B, and broadcasts the message to the whole network. Each active node receives the message. At the same time, each node decrypts the encrypted information using its own private key. Finally, B successfully decrypts the information using its own private key. Since each node receives encrypted messages, the identity of the receiver ensures anonymity.

In the digital signature scenario, sender A of the message hashes the information to get the information abstract. A uses its own private key to encrypt the digest and broadcasts the digest ciphertext to the whole network node. After each node receives the information, the node splits the information and the summary ciphertext, and then hashes the information to get the comparison results. A public key is used to decrypt the digest ciphertext, and the decrypted digest ciphertext is compared with the control result. If they are the same, the sender's information is not tampered with. Digital signature ensures the security of information. Receiver B can make it clear that the information is sent by sender A.

D. Power Ownership Key

In order to prevent double payment of electric energy and determine the ownership of electric energy, the microgrid electric energy trading system predicts the generation of electric energy in the next period of each prosumer before the generation of electric energy. It generates two unique keys b_α and b_β corresponding to the energy E generated by prosumer B, which are sent to the corresponding prosumer and recorded in the database. The generation formulas b_α and b_β are as follows:

$$\begin{aligned} b_\alpha = SHA256(pubKeyB \,||\, E \,||\, pubKeyPPB \\ ||\, Timestamp) \end{aligned} \tag{5}$$

$$b_\beta = SHA256(b_\alpha \,||\, RandomNumber) \tag{6}$$

pubKeyPPB is the public key of photovoltaic power supply equipment corresponding to prosumer B. The former is a static key used to verify B's ownership of saleable energy E. The latter is a temporary key for locking to prevent double payment of energy E. If E is not locked in when dealing with consumers, prosumers may sell the same amount of energy to other consumers. The function of the power ownership key is to quickly verify the user's right to use the power. Whoever owns the power ownership key has the right to use the power. Correspondingly, the auction of electricity will be converted into the auction of the power ownership key.

III. Power Decentralization Trading Method Based on Blockchain

The method of power decentralization based on blockchain can be divided into four steps: energy forecasting stage, transaction matching stage, multi-signature transaction stage, and ownership key replacement stage. Suppose A is a consumer, B is a prosumer, and C is a blockchain system administrator.

A. Energy forecasting stage

In each energy transaction, in order to protect the privacy of both parties and ensure the anonymity of the transaction, A and B will use the corresponding public key and private key to create a pair of new addresses TAddr and MAddr. TAddr is used to execute transactions, and MAddr is an anonymous information address for sending anonymous messages. At the beginning of the new auction, Administrator C predicts the saleable electricity quantity E of prosumer B.C generates two unique keys b_α and b_β of energy E sold by prosumer B and records them in the database. Administrator C uses MAddrC to send b_α and b_β to the address MAddrB of prosumer B. Prosumer B broadcasts auction information to the whole network using MAddrB.

Prosumer B broadcasts function $\mathrm{BROADCAST}(\mathrm{E, P, TAddrB, MAddrB})$, including saleable energy E, reserved price P, transaction address TAddrB and MAddrB anonymous message flow address.

B. Transaction Matching Phase

After prosumer B broadcasts the auction information to the whole network using MAddrB, each node will receive the broadcast information of prosumer B. If consumer A wants to participate in the bidding for power from prosumer B, A will send a message to administrator C using anonymous address MAddrA to verify B's ownership certificate of energy E. Administrator C verifies the database records and replies to the true or false. After successful verification, A will bid for the electricity sold by B. A uses anonymous address MAddrA to send anonymous bidding information to administrator anonymous address MAddrC, where the bidding function is: $\mathrm{MATCH(MAddrA, MAddrB, E', P')}$. Administrator C distributes electric energy according to the sales information and bidding information received. Specific electric energy auction methods are described below.

C. *Multi-signature transaction stage*

After the completion of the power auction, administrator C will broadcast the auction results to the whole network, where the broadcast function of the auction results is $\mathrm{RESULT}(\mathrm{MAddrA}, \mathrm{MAddrB}, E', P')$ .In order to prevent double payment of power E', the system locks power E', and the lock request message is sent to administrator C by prosumer B, which contains b_β key to prove the ownership of B. The lock request is unlocked until the power transaction succeeds and the ownership of the energy is changed.

After power E' is locked, consumer A creates a multi-signature transaction using TAddrA address and sends the designated token to the multi-signature address. The redemption script is as follows:

$$\begin{aligned} rScript = {} & OP\_2 < PubKeyC >< PubKeyB > \\ & < PubKeyA > OP\_3 \\ & OP\_CHECKMULTISIG \end{aligned}$$

Consumer A calculates the redemption script hash $\mathrm{rScriptHash}$ and generates the output script as follows:

$$\begin{aligned} pubScript\ & OP\_HASH160\ < rScriptHash > \\ & OP\_EQUAL \end{aligned}$$

When the multi-signature script is created, A sends $\mathrm{rScript}$ to B's anonymous information address MAddrB . After B receives the information, it is necessary to check whether the script contains its own public key and administrator C's public key, and then run the hash operation to generate the signature script. When a party has doubts about the running status of the multi-signature script, it has the right to provide evidence to the administrator to apply for judgment. Administrator C relies on the running status of the script to process the transaction.

Redemption scripts can be unlocked by scripts containing signatures, where OP_0 is a placeholder.

$$\begin{aligned} & OP\_0 < SignatureA >< SignatureB >< SignatureC > \\ & \quad OP\_2 < PubKeyC >< PubKeyB >< PubKeyA > \\ & \quad OP\_3\ OP\_CHECKMULTISIG \end{aligned}$$

Two scripts, $\mathrm{sigScript}$ and $\mathrm{pubScript}$, form a validation script:

$$\begin{aligned} & OP\_0 < SignatureA >< SignatureB >< SignatureC > \\ & \mathrm{OP\_2} < PubKeyC >< PubKeyB >< PubKeyA > OP\_3 \\ & OP\_CHECKMULTISIG\ OP\_HASH160 < rScriptHash > \\ & OP\_EQUAL \end{aligned}$$

The node verifies the ownership of the asset according to the validation script. When the node is verified successfully, it is proved that prosumer B can use $\mathrm{rScript}$ and signature to obtain the right to use the multi-signature transaction assets.

D. *Ownership Key Replacement Phase*

If there is no dispute between the two parties, prosumer B will use MAddrB to send the ownership key b_α and $\mathrm{pubKeyPPB}$ to the anonymous message address of consumer A. A will use MAddrA to send the request $\mathrm{H}(b_\alpha, \mathrm{pubKeyPPB}, \mathrm{unlock}, \mathrm{update})$ for changing the ownership key to administrator C. Administrator C will receive the information and verify b_α, and unlock the power and generate a new key a_α and a_β corresponding replacement b_α and b_β. Meanwhile, Consumer A signs the multi-signature transaction. At this time, the power ownership of the transaction belongs to consumer A. Consumer A can use a_α and a_β to consume energy E' . At the same time, the property ownership of the multi-signature transaction belongs to prosumer B.

$$\begin{aligned} a_\alpha = SHA256(& pubKeyA \,||\, E' \,||\, pubKeyPPB \\ & ||\, Timestamp) \end{aligned} \tag{7}$$

$$a_\beta = SHA256(a_\alpha \,||\, RandomNumber) \tag{8}$$

IV. ELECTRICITY AUCTION ALGORITHMS

Electric energy auction mechanism can complete the matching of micro-grid electric energy. The blockchain information system collects the auction information of prosumers and consumers and the auction information of consumers, and calculates the auction results. The main function of the electric power auction algorithm is to calculate the set of consumers that each prosumer wins the auction, and to broadcast the successful price of electricity for consumers.

A. *Overview of Auction Algorithms*

The auction algorithm is as follows: the set of prosumers is N, and the set of consumers is M. Assuming that the time of a day is evenly divided into t slots, the set of time slots in a day is recorded as T. The energy forecasting system predicts the next time slot generation $E_n^{'t}$ of prosumer n in advance. Prosumers predict the energy $E_n^{"t}$ consumed by themselves in the next time slot, so the amount of electricity to be auctioned by prosumers n is $E_n^t = E_n^{'t} - E_n^{"t}$. The prosumer submit the sold electricity E_n^t and the reserve price P_b to the blockchain, and the reserve price is the lowest transaction price. Consumer m chooses a number of bidding power according to the sale information, and the bid for each prosumer is sent to the blockchain in the format of (m, n, E_m^n, P_m^n) , where n is the encrypted address information of the prosumer, m is the encrypted address information of the consumer, E_m^n is the bidding power to the prosumer, and P_m^n is the price.

Suppose that set B is a bidding set, and the successful bidding set of consumers is W_n, where $B = \left\{(m, n, E_m^n, P_m^n) \mid n \in N, m \in M\right\}$, $b_{dx} = (m, n, E_m^n, P_m^n)$.

$B_d = \{b_{d1}, b_{d2}, b_{d3}, ..., b_{dx}\}$ is obtained by ordering the bids in a monotonous decreasing order. Then the set B_d should be traversed sequentially. When E_n^t is sufficient, b_{dx} is included in W_n and other bidding information of the user in Set B_d is removed. When the bidded power E_n^t is insufficient, the current b_{dx} in set B_d is removed and the bidding information is skipped. The final set W_n is the successful bidding consumers corresponding to each prosumer. After the auction deadline, the blockchain sends the final auction results to the corresponding prosumers and consumers, including the corresponding consumers who win the auction, the quantity of electricity auctioned by consumers and the unit price.

If consumers do not bid enough electricity, they can choose to buy electricity from the grid at a price of P_g. When photovoltaic power generation is sufficient to meet all consumers in the microgrid, the surplus electricity can be sold to the higher grid at the price of P_b. In general, $P_g > P_m^n > P_b$, therefore, prosumers in order to get more benefits. Consumers spend less on electricity. Both sides of the transaction hope to conduct electricity trading within the microgrid, which can promote consumption within the microgrid.

B. Bidding Strategy

When consumers participate in the auction, they need to estimate the value of electricity roughly. It is assumed that the consumption factor λ is a systematic prediction of consumer consumption impulse in the next period, in which the value of λ ranges from 0 to 1. When λ=0 indicates that the consumer's desire to buy is not strong, the value of electricity to the consumer is relatively low. When λ =1 indicates that consumers are interested in purchasing, and the demand may reach the maximum amount of electricity they consume, then the electricity consumption has a relatively high value to the consumers. From the above, it can be seen that the value of electricity to consumers is closely related to λ. It is assumed that there is a linear relationship between the value of v and the consumption factor λ as follows:

$$v = \lambda(P_g - P_b) + P_b \tag{9}$$

v means that consumers value electricity in this time slot. P_g is the price of power grid, P_b is the reserve price or the price of Internet access. At this point, when λ=0, consumers value electricity as P_b. When λ=1, consumers value electricity as P_g.

According to the bidding rules of the above assumptions, the higher the λ, the higher the valuation. The higher the consumer's valuation, the higher the price that consumers need to win the bidding and the more electricity they need. Suppose there is a linear relationship between demand Q and valuation v as follows:

$$Q = (Q_g - Q_b)(v - P_b) / (P_g - P_b) + \lambda Q_b \tag{10}$$

Among them, Q is the demand of consumers at this time gap, Q_g is the highest consumption of electricity for consumers, Q_b is the lowest consumption of electricity for consumers. According to the above formula, when the user's evaluation is P_b, Q=0, the user's interest in purchasing electricity is small, Q is the lowest consumption of electricity: when the user's evaluation is P_g, $Q=Q_g$, the user's interest in purchasing electricity is large, and will achieve the highest consumption of electricity.

V. EXAMPLE VERIFICATION

Suppose a simple microgrid consisting of prosumer 1-3 and consumer A-F. The token is T. It is assumed that prosumers can predict that the saleable electric energy in each time interval is 100kW • h according to the system. The reserved electricity price for prosumers is set at 0.5T/kW • h and the electricity price for power grid is 1T/kW • h. Since consumers in the microgrid can get all the electricity they need from the grid, consumers who have not won the auction default to buy electricity from the grid at the price of the grid in the auction algorithm. Suppose that the corresponding value of consumers' income to consumers is shown in Table I.

TABLE I. VALUE OF CONSUMER INCOME

Consumer	Prosumer 1	Prosumer 2	Prosumer 3
A	1	0	0
B	0	1	0
C	0	0	1
D	1	0	0
E	0	1	0
F	0	0	1

Assuming that the maximum consumption power of consumer A-F is 200 kW • h and the minimum consumption power is 20 kW • h, the consumption factors λ of consumer A-F are 0.1, 0.2, 0.3, 0.4, 0.5, and0.1, respectively. According to the valuation formula (9) and demand formula (10), the price quotation and demand of consumers for electricity can be calculated, as shown in Table II.

TABLE II. CONSUMER QUOTATION AND DEMAND

Consumer	Valuation (T/kW·h)	Demand (kW·h)
A	0.55	20
B	0.6	40
C	0.65	60
D	0.7	80
E	0.75	100
F	0.55	20

Assuming that consumers are bidding to all consumers to meet their needs, and the final bidding results are obtained according to the power auction algorithm as shown in Table 3.

TABLE III. INITIAL QUOTATION

Consumer	Prosumer	Price (T//kW·h)	Electricity (kW·h)
E	2	0.75	100
D	1	0.7	80
C	3	0.65	60
B	3	0.6	40
A	1	0.55	20
F	0	0.55	20

The final result of the distribution is that consumers A and D bid for 20kW.h and 80kW.h of the prosumer 1 at a price of 0.55 T/ kW • h and 0.7T/ kW • h, respectively. Consumers B and C bid for the price of 0.6 T/ kW • h and 0.65 T/ kW • h to get the power of 40kW • h and 60kW • h of prosumer 3 respectively. Consumer E bid for 0.75 T/ kW • h to get 100kW.h power for prosumer 2. Consumer F needs to purchase 20 kW • h from the grid at a price of 1 T/ kW • h.

VI. CONCLUSION

The anonymous auction and de-centralized transaction of power are realized based on blockchain and user bidding strategy. Blockchain technology, multiple signatures and anonymous message flows are used to ensure the privacy and security of transactions. The proposed method is validated by a typical case of microgrid power trading. The results show that the proposed method can be used for internal microgrid power trading, and the optimal dispatching results are satisfied to some extent by the rules of auction algorithm. Moreover in the blockchain information system, prosumers and consumers can complete the clearing of transactions without central institutions. Under the protection of multi-signature mechanism, the interests of both parties are guaranteed. This method can meet the needs of small-scale, efficient, distributed and low-cost transactions of microgrid, effectively guarantee the self-consumption within microgrid, and ensure the security and economic benefits of microgrid transactions.

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