Optimal Model for Direct Power Purchase by Large Consumers Based on Blockchain

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***Abstract*—The direct power purchase by large consumers (DPLC) is an important part of the reform of the electricity market, and the development of renewable energy has led to a trend of decentralization on the supply side. Blockchain, as an emerging distributed database technology, has a good application prospect in the context of the current energy Internet construction. The article first introduces the principle of blockchain technology in detail and analyzes its application value in electricity trading. Starting from the traditional direct purchase transaction model, a framework for direct purchase of electricity for large consumers is proposed. Combining the characteristics of direct power purchase transactions, the distributed consensus mechanism is researched and improved, the smart contract is designed in combination with the transaction process, and the communication protocol and interaction relationship at each level are analyzed from the overall system architecture. Finally, the challenges faced by the system in practical application are analyzed, which provides ideas for follow-up research.**

Keywords—blockchain, electricity markets, direct power purchase by large consumers, market design

I. Introduction

With the development of new energy, direct power purchase by large consumers (DPLC), as a special electricity transaction mode, is increasingly popularized. In tradition DPLC mode, electricity trading is carried out by the central exchange and local agents, and large consumers need to buy from the agents. DPLC refers to a transaction mode in which companies that meet certain power usage conditions directly sign contracts with e-commerce vendors. The traditional DPLC mode mainly include negotiated bilateral transactions and centralized bidding transactions. The former requires face-to-face and independent negotiation between the two parties involved in the transaction, while the latter is done on the trading system based on algorithm matching. The traditional transaction model has the disadvantages of low efficiency, opaque transaction information, and easy data attack. Therefore, research on emerging transaction methods based on blockchain is very important.

As a decentralized, open and transparent database, blockchain technology has unique advantages in transaction records and transactions that have certain requirements for security. Demand for transaction security and convenience makes it necessary to develop a blockchain platform[1]-[2].

In literature[3]-[10], typical blockchain platforms for electricity trading have been established, and combined with the actual project for testing. But no discussion on consensus algorithm and security. In literature[11], the use of blockchain technology, multi-signature and anonymous encrypted message flow has implemented a proof of concept of a decentralized energy trading system, enabling market participants to negotiate energy prices anonymously and execute transactions safely. In literature[12]-[14], discussed the safety protection of blockchain technology for the energy market, analyze from different energy trading fields. However, these models are just simulations of the system, and no specific plans for privacy protection security measures are proposed. In literature[15]-[17], analyzed the impact of different consensus algorithms on the power flow problem of the power grid. Meanwhile, using a blockchain-based Alternating Direction Method of Multipliers and analyze the performance. But these studies did not about DPLC transaction types.

This paper will analyze the typical links and policies of DPLC on the basis of introducing the principle of blockchain, from chain structure, consensus mechanism to smart contract construction, and propose a DPLC model based on blockchain. The actual simulation simulates specific transactions and realizes a new type of open, transparent, and highly convenient direct purchase transaction system.

II. An Overview of Blockchain

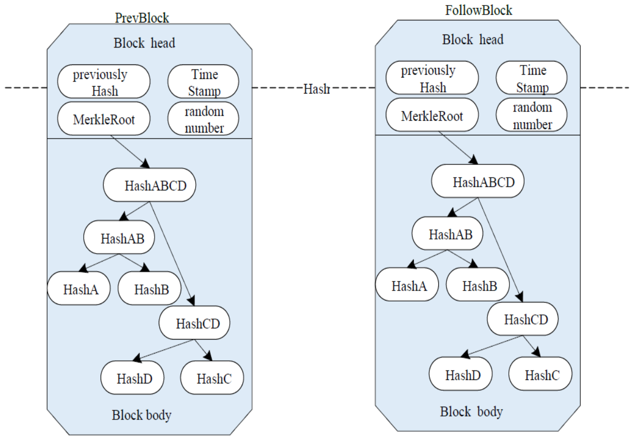

Fig.1 Basic structure of the block

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As a new type of segmented database technology, blockchain technology has attracted much attention since it was proposed. Under the concept of blockchain, all nodes in the network share the storage of data, making it a trusted and safe system [18]-[19].

As the basic structural unit of the blockchain, a block is a series of data blocks obtained by using an encryption algorithm[20]. The connection model is shown in Figure 1. Each block contains basic data such as transaction information, Merkel root, timestamp, and the hash value of the previous block. All blocks are connected end to end to become a complete block chain, and tampering with the value of the block will cause all subsequent blocks to be changed. This structure fundamentally guarantees the security of the data[21].

It can be seen from the data structure of the blockchain that once the security of a block is not guaranteed, its immutability will no longer exist[22]. Blockchain mainly uses two encryption algorithms to ensure data security: hash algorithm and asymmetric encryption technology[23]. Apply a hash algorithm in the block to calculate the hash value of the current block, and calculate the hash value of each transaction in the Merkel tree. The asymmetric encryption algorithm is used in the transfer transaction. Its operating principle is shown in Figure 2. Each user is assigned a public key and a private key. When the user writes data, the private key is used for digital signature. Based on the blockchain network, the signature is And the transaction content is sent to the receiving user. Accept the user to confirm the data by decrypting the digital signature and the transmission content and comparing the digest content.

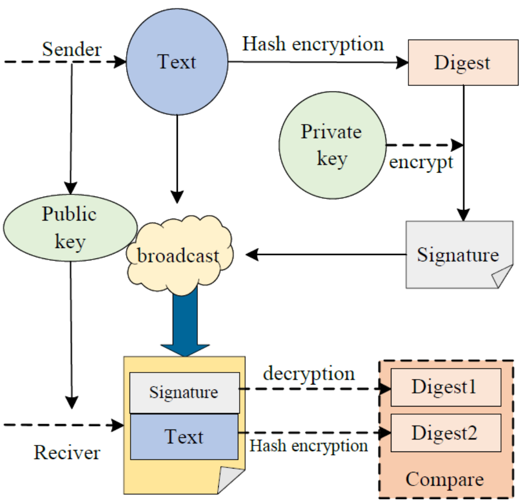

Fig.2 Principles of Blockchain Encryption

The consensus mechanism is an algorithm for each node in the blockchain to confirm transactions and reach a consensus. For a distributed ledger system such as the blockchain, the consensus mechanism can complete the data synchronization of all nodes, and can ensure that the transaction data is not tampered with, which is a guarantee for the safe and stable operation of each node. At present, the main consensus algorithms mainly include POW (Proof of Work), POS (Proof of Stake), DPOS (Delegated Proof of Stake), distributed consensus algorithm, etc.

III. Detail Description

A. *Direct Power Purchase Model for Large Consumers*

Participants in the traditional direct purchase of electricity by large consumers mainly include large consumers, power generation companies and trading institutions. Large consumers and generators that meet the access mechanism directly sign electricity purchase contracts[24]. This approach breaks the original monopoly pattern and can effectively reduce the power purchase cost of enterprises. This transaction model can be divided into direct purchases by large consumers in the province and direct purchases across provinces. According to the transaction method, it can be divided into centralized matching transaction, centralized bidding transaction and centralized listing transaction. The trading center is responsible for publishing transaction content, and companies and power generators participating in direct purchases submit transaction requirements within a specified time. The transaction center determines the two parties to the transaction according to a certain matching method. The dispatch center conducts safety check and congestion management on the matched transaction, and obtains the restricted transaction result, and finally the dispatch agency conducts power transmission according to the signed contract. Its structure is shown in Figure 3.

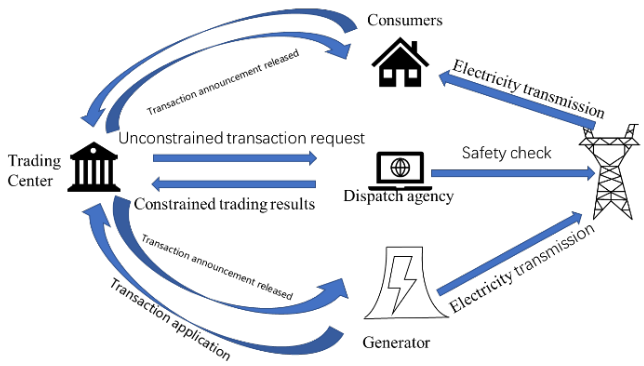

Fig.3 Traditional direct power purchase model

Participants of the large-user direct power purchase system established in the article mainly include three parts: large users and generators of the transaction subject, and power grid companies responsible for management. When the entire power system conducts power transactions to realize the flow of power and funds, the interaction of node information is carried out. In order to combine the background of the quota system to promote the consumption of new energy under the direct power purchase mode, a framework structure with two chains on the main and side chains is adopted[25]. The main chain is responsible for direct purchase transactions with high transaction volume, and the side chain is responsible for completing the green certificate transaction. The link between the two chains can be completed by two-way anchoring technology. The system link structure is shown in Figure 4.

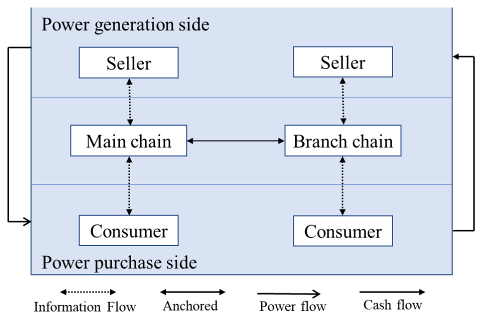

Fig.4 Direct Power Purchase Link Model

B. *Improved Raft Consensus Mechanism*

RAFT is an improved algorithm for PAXOS. On the basis of the latter, the algorithm structure is simplified to make it more suitable for the actual production environment. Its core content includes node election, log replication and security assurance. The core nodes are divided into leaders, followers and candidates. Among them, the leader node is responsible for processing the service request of the system client; the follower node is responsible for passively receiving and replying to the information sent by the leader node; when the leader node is in a failure or shutdown state and the node is reselected, the candidate node is in a transitional state.

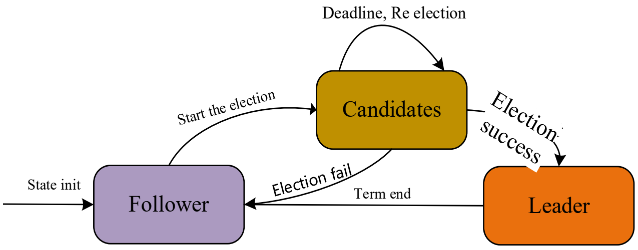

Fig.5 RAFT node election process

The node election process of the traditional RAFT algorithm is shown in Figure 5. When the system is started, all nodes are followers, and a leader node is randomly generated. The leader node will periodically send a response to all followers. When the follower does not receive a response from the leader within a certain period of time, an election will be initiated. Candidates decide their leaders based on their votes. Those who fail the election become followers and wait for the next election to be initiated.

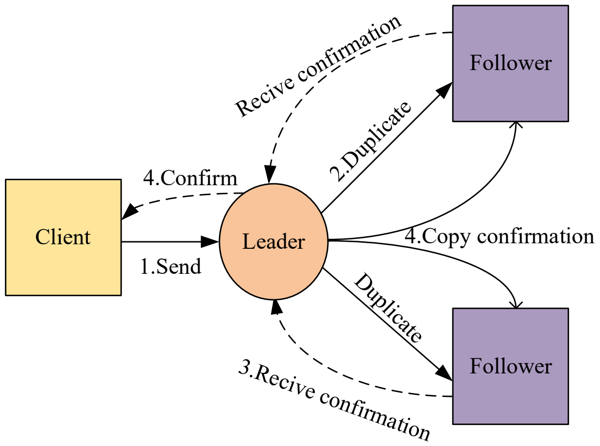

Fig.6 RAFT log copy process

The log replication process is shown in Figure 6. After the leader node is selected, it starts to accept the status response sent by the client. The leader node adds the response as the new content of the log to the original log, and initiates RPC (Remote Procedure) in parallel. Call, remote procedure call) to the follower server, waiting for all followers to copy the log, the response will be added to the state machine of the leader node with the update of the log, and returned to the client.

Based on the structural characteristics of the DPLC, the trading center, as a scheduling and management organization, can provide a stable operating environment and reliable security guarantees. Therefore, the internal nodes of the trading center are considered as candidate nodes for the leader. This method can effectively reduce the amount of communication in the leader node election stage and conforms to the structural thinking of weak centralization. The structure of the improved algorithm is shown in Figure 7.

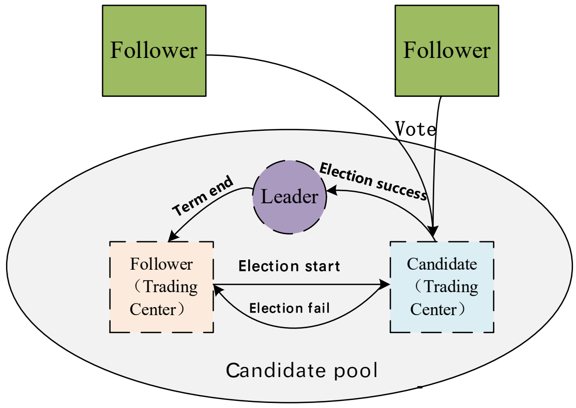

Fig.7 Improved RAFT voting mechanism

The specific process is:

```
Algorithm Improved RAFT
Input: Leader Crash
Output: New leader and its Pool
if θ=False then
    // θ is the signal that the nodes in Table complete the consensus process
    db.log ←rollback //log replica rollback
else
    Pool(i)←random.node()// Randomly select the trading center node i to enter the pool
    x←Pool_max
    //Select a node with the most vote in Pool(i) as the Leader
    Leader←Pool(x)
    makeRefresh() //refresh Candidate pool
     Pool←lookup(Pool, Leader) //update leader centered Improved RAFT
end if
return Leader,Pool
```

C. *Smart Contract Design*

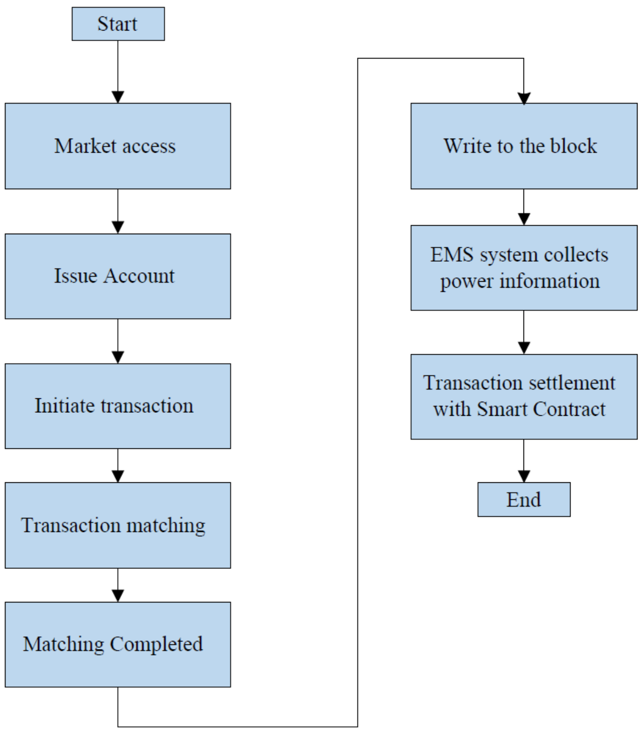

Fig.8 Transaction process

The direct purchase transaction process based on smart contracts is shown in Figure 8. At the beginning of the transaction, all parties involved in the transaction need to submit an access application, and the bilateral transaction matching stage will be carried out after the access review. After the transaction is completed, the data will be recorded in the smart contract and added to the block after the consensus of the entire network nodes. The central agency will conduct a security check on the completed transaction. If it passes, it will directly enter the blockchain for transaction settlement. If it fails, it will undergo blocking management and recheck until it is passed.

- Registration admission stage: By calling the registration function Regis(), consumers and generators convert the balance in their wallets into tokens for exchanges, and set the exchange rate between the tokens and RMB to be 10:1 to confirm the actual transaction Amount, at the same time, confirm your transaction address and code.
- Trading listing stage: According to the traditional DPLC model, both parties to the transaction need to call the listing function PAYMENT() to submit transaction requirements, and the registration information includes; declared electricity quantity and declared electricity price. After registration, the corresponding information will be recorded in the block. Before the listing deadline, both parties can also withdraw the pending order through the transaction withdrawal function WITHDRAW().
- Transaction settlement stage: After the listing time expires, the smart contract automatically calculates the discounted electricity price of each generator, sorts the generators and large consumers according to priority, and finally conducts matching transactions according to the principle of high-low matching. After the transaction is completed, the buyer and the seller call the settlement function TRANS() according to the result of the contract matching to perform the transfer. After the transfer is completed, the next stage of the transaction is opened.

D. Pricing Mechanism

The selling and buying parties determine the individuals for each round of the transaction through a matching matrix, where the matching matrix containing m buyers and n sellers can be expressed as:

$$\left[q_{ij}\right]_{m\times n} \quad (1)$$

$$q_{ij} = q_{A,i} - q_{B,j} - X_{B,j} - Z_{ij} \quad (2)$$

$$X_{B,j} = T_b \bullet P_g \quad (3)$$

In the formula: the social welfare conversion formula is shown in formulas (2)-(3). The matching method is based on the converted value of the two trading parties in descending order. After confirming both sides of the transaction, the row or column is removed from the matrix and the matrix is updated for the next round of matching. The settlement cost for each round of transactions is determined as in formulas (4)-(6).

$$L_i = F_{B,i} - 0.5\Delta f_{ij} \quad (4)$$

$$L_j = F_{S,j} + 0.5\Delta f_{ij}(1-\varepsilon) + X_{B,j} \quad (5)$$

$$\Delta f_{ij} = f_{B,i} - \frac{F_{S,j}}{1-\varepsilon^*} + S^* + W \quad (6)$$

In the formula: L_i is the settlement price for large consumers of inter-provincial transactions. L_j is the settlement price for generators of inter-provincial transactions. $F_{B,I}$ is the electricity purchase price submitted by large user i to the weakly centralized node of the blockchain. $F_{S,j}$ is the electricity sale price submitted by large user j to the weakly centralized node of the blockchain. ε* is the inter-provincial transmission loss. S* is the inter-provincial transmission price. W is environmental protection price and cross subsidy fee.

IV. Result

In order to verify the effectiveness of the direct purchase transaction model proposed in this paper, this chapter simulates each electricity market counterparty in multiple computers, builds up a blockchain for DPLC, deploys contracts into the server, and each participant implements the corresponding functions by invoking the contracts.

Suppose there are four wind power generators W1-W4 and four thermal power generators H1-H4 in region A. The large consumers are B1-B2 in region B, C in region C and D in region D. The wind and fire baling ratio is 1:3. Also let the standard green certificate price P be 19 Token/book and t=book/MWh. Wind power companies will obtain one certificate for every 1MW of production, and thermal power companies will consume 0.2 certificates for every 1MW of production. The inter-provincial network loss rates and transmission prices are shown in Table 1:

Table.1 Network loss rate and transmission cost

Counterparty's location	Network loss rate (%)	Transmission cost (token•(kW·h)$^{-1}$)
A-A	2	0.2
B-B	2	0.2
C-C	2	0.2
D-D	3	0.3
A-B	6	0.8
A-C	7	1
A-D	6.5	0.9
A-A	2	0.2

In order to analyze the transaction advantages of the large user direct purchase system based on the blockchain mode, the article considers whether the blockchain participates in the next two transaction scenarios.

Case A: The traditional large user direct purchase model that does not include green certificate transactions, the wind-fire bundling ratio is 1:3, and the matching is confirmed according to the traditional high-low matching method. After confirming the transaction partner, simulate the initiation of an electronic contract through the simulation platform, and the transaction center will complete the matching transaction after verification, and the transaction funds will be managed by the transaction center;

Case B: Direct purchase model for large users based on blockchain technology. In order to study the impact of green certificates at different prices on transactions, set the prices of green certificates as 300 Token/this, 400 Token/this, and 500 Token/this respectively. According to the standard, every 1 MW of green power produced will receive a certificate, and every 1 MW of thermal power produced must be paid 0.2 certificates. According to the process shown in Figure 6, when the quota for large users is met, green e-commerce can sell the excess green energy on the green certificate market to obtain additional revenue. Through green certificate chain transactions between power producers, they can meet quota requirements.

Large users submit electricity purchase orders as shown in Table 2. The order form contains the electricity prices and electricity declared by the four user nodes B1-B2, C, and D, as well as the green electricity quota required by each node. The electricity sales orders for wind power and thermal power are shown in Table 3 and Table 4 respectively, including declared electricity price, declared electricity and subsidized price.

Tab.2 Quotations of large consumer

No.	Declared tariff (token/kWh)	Declared electricity (MWh)	Wind power ratio (%)	Wind power demand (MWh)
B1	5.123	17083	20	3425
B2	5.221	24353	15	8932
C	5.134	14892	15	7463
D	5.643	53928	20	4355

Wind power companies submit power sales pending orders as shown in Table 3:

Tab.3 Quotations of wind power companies

Wind power company	Declared tariff (token/kWh)	Declared electricity (MWh)
WI	3.598	3486
W2	3.424	5324
W3	3.511	5828
W4	3.533	7801

Thermal power companies submit power sales pending orders as shown in Table 4:

Tab.4 Quotations of thermal power enterprise

No.	Declared tariff (token/kWh)	Declared electricity (MWh)	Environmental Conversion Price (token/kWh)	Cross-subsidized prices (token/kWh)
H1	3.159	12326	0. 1	0. 1
H2	3.123	32445	0. 15	0. 1
H3	3.165	23198	0. 1	0. 1
H4	3.144	6343	0. 1	0. 1

The trading results of the two schemes are shown in Table 5 and Table 6. Since Case A does not consider green certificate transactions, green energy revenue is less, and the total profit of the power generation alliance is lower. Case B introduces green certificate prices for market incentives, which can not only help wind power to absorb excess electricity, reduce the cost of competition, but also bring additional benefits to wind power companies. From the data of each group, when the price of green certificates increases, the overall market revenue also increases, indicating that the introduction of the green certificate market has a certain incentive effect on the direct purchase model.

Tab.5 Transaction matching results

Matching groups	Large User No.	Sender No.	Traded electricity (MWh)	Buyer Price (token/kWh)	Seller Price (token/kWh)
1	D	W2	4355	4.534	2.314
2	B2	W2	969	4.323	2.525
3	B2	W3	5828	4.366	2.656
4	B2	W4	2135	4.377	2.689
5	B1	W4	3425	4.328	2.738
6	C	W4	2241	4.334	2.733
7	C	W1	3486	4.366	2.830
8	D	H4	6343	4.394	1.895
9	D	H1	12326	4.401	1.917
10	D	H3	23198	4.404	1.926
11	D	H2	7706	4.383	1.863
12	B2	H2	7706	4,383	1.863
13	B1	H2	7706	4.383	1.863
14	C	H2	2332	4.383	1.863

Tab.6 Comparison of transaction results

Case	Green certificate price (token)	Green certificate income (token)	Total wind power profit (token)	Total revenue of generators (token)
Case A	0	0	399913	3060282
Case B	3	32600	405796	3117238
	4	42416	415318	3143720
	5	51145	427163	3176196

Through the comparison between the traditional model and the transaction model proposed in this paper, the feasibility of the blockchain-based power transaction model is verified. The block chain-based direct purchase transaction system can realize functions such as electric energy transaction and green certificate management. Compared with traditional direct purchase transactions, this model can effectively avoid malicious competition, and distributed data storage can enhance transaction security. In addition, the digital platform based on the registration mechanism can also prevent data from being tampered with and viewed by non-registered users.

V. Conclusion

This paper studies the operation model of the large-user direct-purchase power market supported by the blockchain. Based on the traditional consensus mechanism, it designs a consensus mechanism suitable for DPLC and the overall market framework and discusses the specifics of power transactions within the direct-purchase framework. The process is introduced, and the blockchainization of power transactions is combined with smart contracts, and simulated transactions are realized by calling contract functions to ensure the openness and convenience of direct purchase transactions. Distributed storage and data management systems such as block chain can bring rich expansibility and openness to direct purchase transactions, which is conducive to mobilizing market efficiency and saving transaction costs.

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