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A blockchain-based smart contract trading mechanism for energy power supply and demand network

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ABSTRACT

To overcome the high cost, high risk and poor efficiency of traditional centralized electric energy trading method, this paper proposes an efficient trading mechanism for energy power supply and demand network (EPSDN) based on blockchain smart contract, considering the opening of the sales side market in China. Specifically, the encourage-real-quotation (ERQ) rule was adopted to determine the clearing queue and price, thus smoothing the supply and demand interaction between the EPSDN node. Meanwhile, the blockchain smart contract was introduced into the transaction to form a sealed quotation function, which eliminates the centralization and high cost and solves the poor transparency and trust in traditional transaction. In addition, the transaction efficiency was improved through the construction of an efficient power trading system and a secure trading environment. A case study is given in the end of the paper. Case study shows that the blockchain-based smart contract trading system for the EPSDN can achieve desirable security and effectiveness, and effectively solve the problems of the traditional centralized trading method. The research findings lay solid theoretical and decision-making bases for small-scale transactions in the electric energy market.

ARTICLE INFO

Keywords:
Electric energy;
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Blockchain;
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1. Introduction

In March, 2015, China released the several opinions of the Central Authority of China and the State council on further deepening the reform of the power system, kicking off a new round of power system reform. Focusing on "control the middle and liberate the two ends", the new round of reform allows "sales side" market, distributed generation (DG) energy and other entities to participate in market competition.

The rapid development of the Internet and technologies not only diversifies the DG energies, but also greatly improves generation efficiency and suppresses production cost of such energies. Against this backdrop, numerous households have acquired the independent generation capacity. With the gradual opening of the sales side market, many small power supply and demand units (SDUs) from the grid, especially the distribution network, will join the power market. This calls for an efficient power trading system to enhance the consumption rate of DG energies [1].
Security, transparency and efficiency are the key to building a power trading system. Currently, most power transactions between the SDUs are carried out through the trading center. The centralized trading method is not transparent and prone to data leakage if the central node is under malicious attack, which poses a serious threat to the maintenance of the trading system [2]. After the full opening of the sales side market, the power trading system will be thronged with small SDUs from the distribution network. The power generation of these SDUs are highly uncer-

tain, so is their power consumption. For example, the wind-solar hybrid power generation depends heavily on the weather condition. The SDUs will submit lots of small orders to the trading center, leading to high cost, poor efficiency and prolonged decision-making. What is worse, the SDUs will not publish all the information to the trading center due to the lack of trust. In addition, it is difficult to guarantee the safety of the data- and fund-rich trading center, which is very vulnerable to malicious attacks.

The blockchain smart contract provides a decentralized, trust-free and traceable solution to the high cost and high risk of the centralized trading method [3, 4]. Much research has been done on energy blockchain at home and abroad. Considering the opening of the sales side market, some scholars put forward automatic demand response methods based on blockchain technology, and introduced the workload proof mechanism, smart contract and information security of the response process [5-7]. Hussein *et al.* [8] explores how blockchain-based smart contracts improve the transaction efficiency in the power market, and discusses the key technical difficulties. Jian *et al.* [9] designs a liquidation model for the power market with limited competition based on the market equilibrium principle in microeconomics. Li *et al.* [10] reviews the key techniques and potential applications of automatic demand response methods related to smart contracts. These results provide a strong impetus to the research of energy blockchain, and offer valuable references for further optimizing the smart contract trading mechanism in the power system. Nevertheless, the existing studies mostly stop at feasibility analysis, failing to explain the realization of theories; there is no report on the implementation of power trading systems, which are theoretically constructed based on smart contract.

To make up for the above defects, this paper proposes an efficient trading method for the power market based on smart contract, considering the immense popularity of DG energies. In this method, the trading parties and price are determined by the encourage-real-quotation (ERQ) rule; the security, transparency, fairness and efficiency of the transaction are ensured by the transaction method based on smart contact; the transaction efficiency of the power trading system is guaranteed by the decentralized and trust-free features. The proposed trading method was proved decentralized and efficient through example analysis. The research findings provide a valuable reference for small-scale transactions in the power market.

2. Energy power supply and demand network (EPSDN)

The SDUs, as the main players in the EPSDN, can be divided into production units and consumption units according to their varied demands at different times. The two types of units respectively belong to the supply side and the demand side [11, 12].

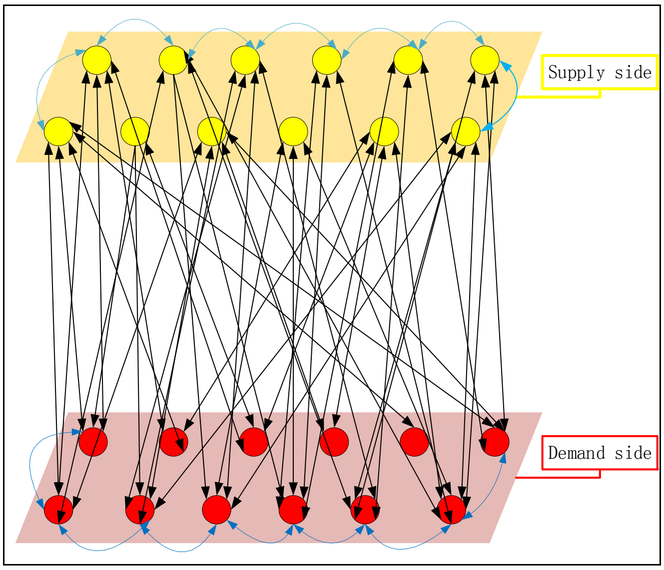

Fig. 1 The energy power supply and demand network (EPSDN)

At a certain moment, some SDUs need to purchase power to maintain their normal working and living while some need to sell the excess power produced by them. In this case, the former SDUs are consumption units while the latter are production units. The two types of units are not fixed, but changing and interacting over time. The units are connected to each other, forming an EPSDN (Fig. 1).

The SDUs can also be split into primary units and secondary units. In the EPSDN, large power plants and large users are primary units, while small power plants and ordinary users are secondary units. For simplicity, all the SDUs in the EPSDN are hereby regarded as primary units.

Fig. 2 shows the SDU structure in the blockchain-based EPSDN [13, 14]. There are four layers of an SDU: the encryption layer containing the hash function value related to the sealed quotation, the real quotation and a random string; the block layer that saves the information of each transaction and forms the blockchain; the temporary storage layer that temporarily stores transaction information; the variable layer consists of the variables in the SDU state space.

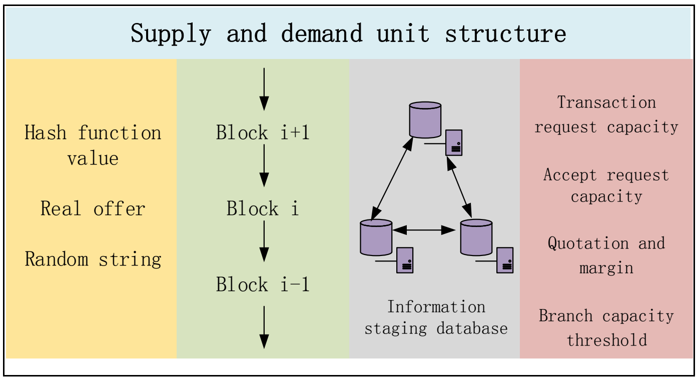

Fig. 2 The supply and demand unit (SDU) structure

The SDUs obey the following interaction rules in the EPSDN:

- After a consumer unit issues a transaction request to the entire network, the production units will determine whether to accept the request according to their own capacities.
- The production units accepting the request need to quote through a hash function.
- If the quotation is appropriate and does not exceed the branch capacity thresholds of both parties, the two parties will interact successfully.
- The relevant interaction information will be uploaded to the information database, and the generated block will be connected to the blockchain.

3. Trading system and ERQ rule

3.1 Trading system

If the EPSDN is dominated by DG energies, there will be strong uncertainties in the production and consumption of the SDUs. In this case, the traditional centralized trading method faces high risk and poor efficiency [15, 16]. Based on the EPSDN, this paper adopts the ERQ rule to determine the clearing queue and price and creates an efficient and flexible power trading system to achieve the real-time balance between production and consumption.

As shown in Fig. 3, the EPSDN power trading system can be divided into a primary power market and a distributed multilateral trading market. The primary power market is mainly responsible for the day-ahead transactions. In this market, the SDUs submit their day-ahead production and consumption plans to the trading center, which then determines the initial production and consumption units according to the plans. The distributed multilateral trading market mainly adjusts the difference between the supplied amount and the sold amount (hereinafter referred to as the power difference). The transactions between the SDUs are point-to-point and traceable. In the final phase, the power difference is eliminated by the backup unit in the system.

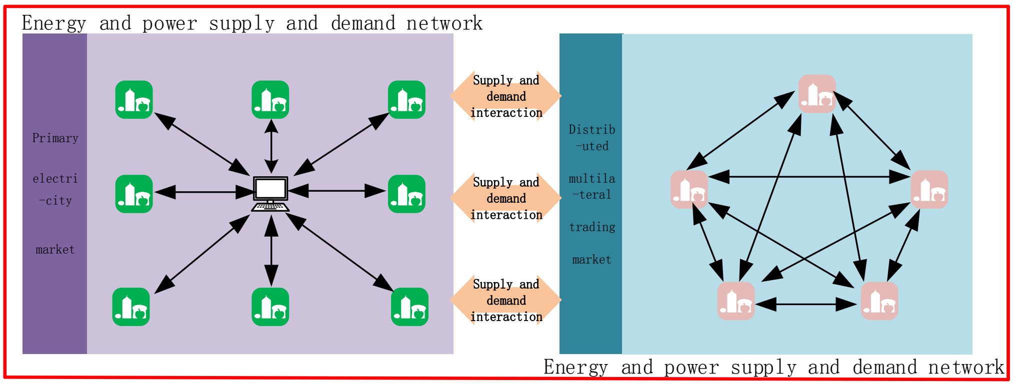

Fig. 3 Power trading system

3.2 ERQ rule

The core idea of the blockchain-based efficient power trading system is to encourage the real quotations of the SDUs participating in the power market. Following the ERQ rule, the SDUs can complete the transactions timely and accurately according to the submitted data, thus improving the success rate of the transaction and striking a balance between supply and demand. The specific process of the EQR is detailed below.

The EQR scenario is that the production units submit the quotations after the consumption unit issues a power purchase request. This scenario aims to maximize the revenues of the power trading market, while eliminating the power difference in the system. The objective function of the model can be expressed as:

$$\max\left(\sum_{i\in\Pi_p}\left(F_i(Q_{i,p})-f_i(Q_{i,p})\right)+E_p\right) \tag{1}$$

where, Π_p is the set of production units; $F_i(\bullet)$ and $f_i(\bullet)$ are the sales revenue function and sales cost function of the i-th production unit, respectively; $Q_{i,p}$ is the for-sale power provided by the i-th production unit (obviously, $Q_{i,p} > 0$); E_p is the revenue of the backup unit.

The model is subjected to the following constraints:

Power difference balance:

$$\sum_{i\in\Pi_p} Q_{i,p}-\sum_{i\in\Pi_c} Q_{i,c}+Q_s=0 \tag{2}$$

where, Π_c is the set of consumption units; $Q_{i,c}$ is the power demand of the i-th consumption unit; Q_s is the power consumption of the backup unit. If $Q_s > 0$, the for-sale power is smaller than the power demand, and the gap needs to be eliminated by the backup unit; if $Q_s < 0$, the for-sale power is greater than the power demand, and the excess power needs to be consumed by the backup unit.

The upper and lower bounds of the for-sale power provided by production units:

$$Q_{i,p.\mathrm{min}} \le Q_{i,p} \le Q_{i,p.\mathrm{max}}, \forall i \in \Pi_p \tag{3}$$

where, $Q_{i,p.\mathrm{min}}$ and $Q_{i,p.\mathrm{max}}$ are the upper and lower bounds of the for-sale power provided by the i-th production unit, respectively.

Line transmission capacity:

$$\sum_{i\in\Pi_p} Q_{i,p}W_{xy,i}+Q_sW_{xy,i} \le \overline{Q_{xy}},\ \ \forall xy\ \in L=0 \tag{4}$$

where, $W_{xy,i}$ is the energy transfer distribution factor of node i to line xy; L is the set of all lines in the system; $\overline{Q_{xy}}$ is the transmission capacity limit of line xy. The value of $W_{xy,i}$ can be determined by:

$$W_{xy,i} = \begin{cases} 1, \text{located at the starting point} \\ 0, \text{located at the branch} \\ \text{-}1, \text{located at the end point} \end{cases} \tag{5}$$

Eq. 5 gives the values of the energy transfer distribution factor at different conditions. The value of the factor is one if node i is located at the starting point of line xy, zero if node i is located at the branch of the line, and -1 if node i is located at the end point of the line.

3.3 Operating mechanism

Our operating mechanism introduces blockchain smart contract into the traditional trading method, and implements the ERQ rule to ensure the self-sufficiency of the SDUs in the EPSDN, as well as maintaining the supply-demand balance, reducing costs and increasing revenue [9]. There are many advantages of this novel operating mechanism. For instance, the SDUs in the system can basically satisfy their own power demand for working and living through self-generation and the help from other units, which ensures the real-time balance of the grid; the social cost is cut down because no special supply is needed from the grid; the SDUs can acquire revenues from mutual assistance and transactions; the operation is efficient, secure and transparent, for the central node is replaced with point-to-point transactions between the SDUs; the supply and demand information is acquired timely, making it possible to consume the excess DG energies in the SDUs and eliminates the power difference in real time; the operating mechanism also promotes the development and use of clean energy, because most of the DG energies are clean in nature. The operating mechanism of the power trading system is illustrated in Fig. 4.

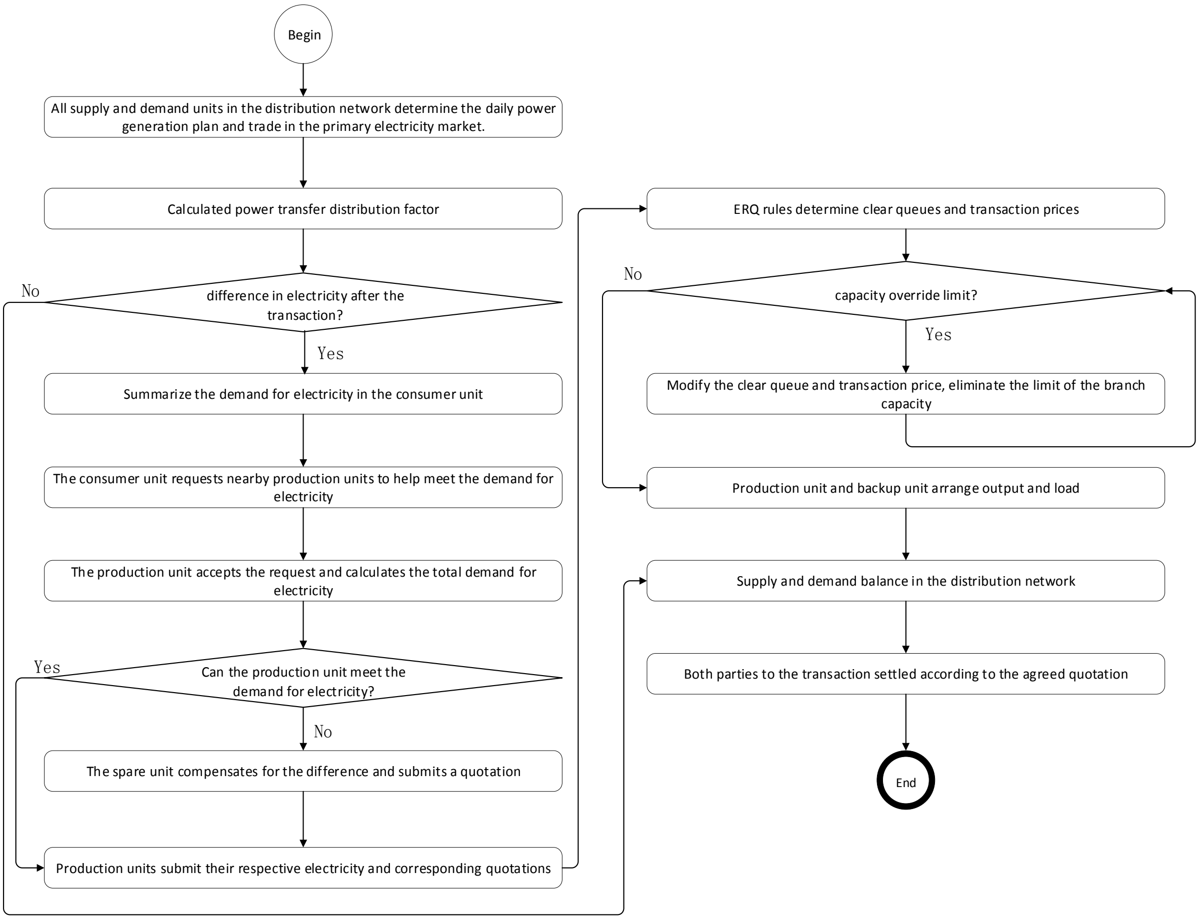

Fig. 4 Operating mechanism of the power trading system

The specific steps of the operating mechanism are as follows:

Step 1: All the SDUs in the distribution network determine the day-ahead production and consumption plans, and carry out preliminary transactions in the primary power market.

Step 2: An SDU will become a consumption unit if it demands more power than the planned production for the day, and will request other SDUs in the system to satisfy its demand.

Step 3: Each nearby production unit accepting the request will calculate the total power demand and judge whether it can fully satisfy the demand. If yes, the production unit will directly submit the available power and quotation; otherwise, the production unit will request the backup unit to compensate for the gap and submit the quotation.

Step 4: All quotations are cleared according to the ERQ rule: All valid quotations are ranked in ascending order until the power difference is eliminated.

Step 5: The power transfer distribution factor is calculated to judge whether the power exceeds the transmission capacity limit of any line. If not, the security review is passed and the next step will be executed; if yes, the clearing queue and price will be modified to reduce the power transmitting through the line. The modification steps include (1) computing the capacity ΔQ_{xy} of the target line xy; (2) increasing the quotation of the production unit at the start point of the line until the line capacity is reduced to ΔQ_{xy}; (3) repeating Step 4 to confirm the transaction price and repeating Step 5 until the power does not exceed the transmission capacity limit of any line.

Step 6: The production unit and backup unit participating in the transaction will arrange the output and load to ensure the supply-demand balance of the distribution network.

Step 7: Both parties will settle according to the agreed quotation.

4. Efficient trading mechanism based on smart contract

4.1 Smart contract

Blockchain, a revolutionary technology in the Internet era, adopts an underlying decentralized collaboration mechanism. The data are linked up by chronologically generated blocks, forming a data structure suitable for any decentralized trust network. The unique formation mechanism has blessed the blockchain with such features as decentralized, trust-free, traceable and smart contracted [17, 18].

In essence, a smart contract running on a blockchain is a computer program that is automatically executed according to certain rules [19, 20]. Once being reached between the transaction parties in the smart contract, the agreement will be automatically executed by the pre-written code and cannot be intervened. In this way, the contact can be signed and executed more efficiently at a lower. Similar to that of traditional contracts, the lifecycle of smart contract (Fig. 5) involves such three phases as contract generation, contract release and contract execution.

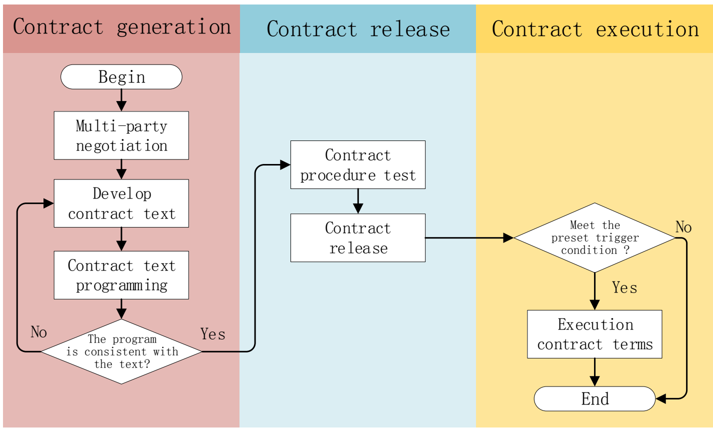

Fig. 5 The lifecycle of smart contract

In the phase of contract generation, the multiple parties need to negotiate over the contract, prepare and routinize contract text, and judge whether the program is consistent with the text. Firstly, the contracting parties should determine their rights and obligations through discussion, and initialize the draft of the contract. Secondly, relevant persons with professional knowledge and legal literacy will review the conformance and legal effect of the draft, and finalize the text in paper. Thirdly, professional technicians will routinize the contract text into a program based on the blockchain, and conduct a trial run on the virtual machine to check the consistency between the program and the text. If consistent, the next phase will be initiated; otherwise, the above steps need to be go through again.

The contract release is relatively simple. After passing the program test, the contract can be released to all nodes in the network. The contract execution is based on a preset trigger condition. Once the condition is satisfied, all terms in the contract will be executed automatically in an open and transparent manner, and all transaction information will be recorded; otherwise, the program will be terminated immediately.

4.2 Trading mechanism based on smart contract

The trading mechanism based on smart contract should carry the following three features: All SDUs are free to enter and exit the power trading market; the quotation of each production unit is kept confidential before clearing; the relevant terms in the contract should be executed automatically [21].

Here, the trading mechanism is divided into six phases, namely, request issuance, request acceptance, quotation sealing, determination of clearing queue and transaction price (CQTP determination), security review, and transaction settlement. The six phases are corresponding to six performance functions: request issuance function, request acceptance function, quotation sealing function, CQTP determination function, security review function and transaction settlement function. Next, the power difference purchase of a consumption unit was taken as an example to illustrate the execution of smart contract. The transaction process is shown in Fig. 6.

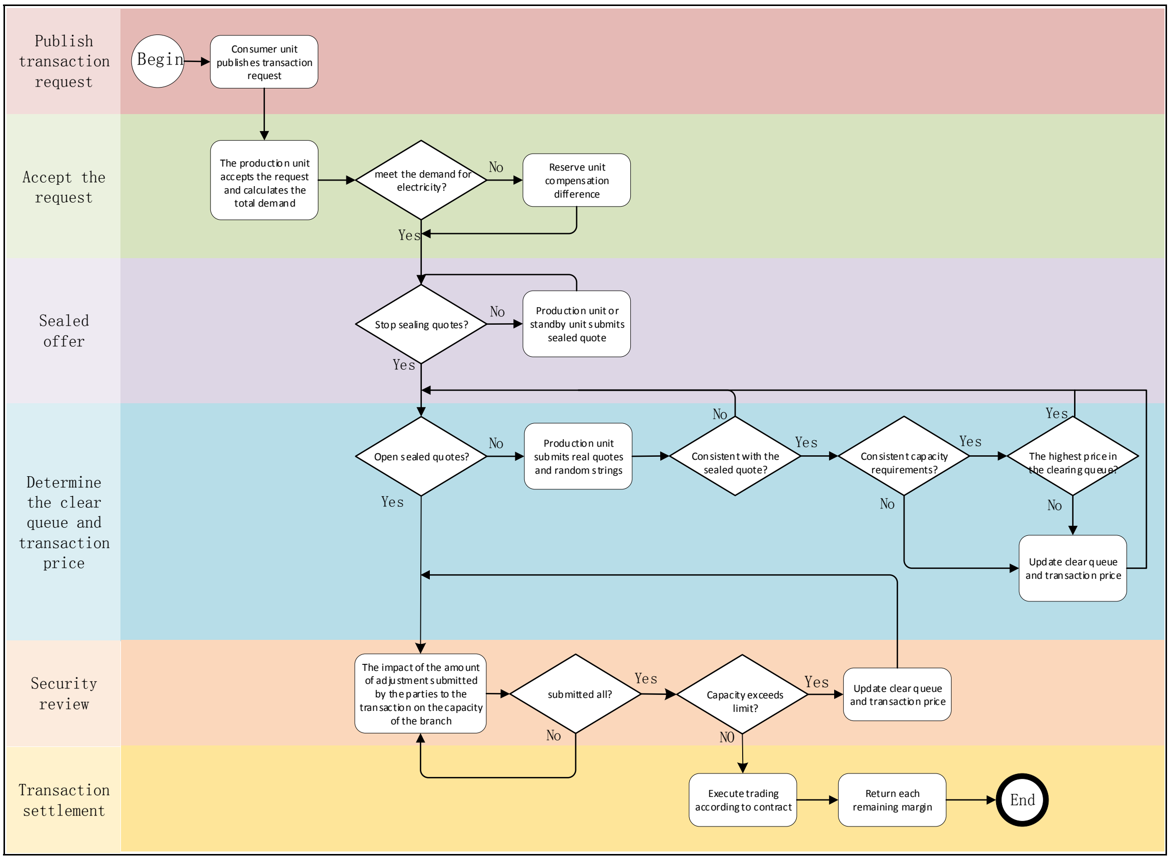

Fig. 6 Smart contract trading mechanism

During the request issuance, any SDU in the distribution network can issue a transaction request as a consumption unit, after transferring a certain amount of virtual currency to the smart contract address. The virtual currency serves as a deposit against false request. In the request acceptance phase, each SDU with excess power in the distribution network automatically becomes a production unit, calculates the total power demand of the consumption unit, and judges if it can satisfy the demand. If necessary, the backup unit will be started to compensate for the gap.

The quotation sealing, the core of the trading mechanism, directly bears on the transaction fairness. Since the smart contract requires the production unit quotations to be kept confidential before clearing, the quotation process was divided into the sealed quotation stage and the public quotation stage. In the sealed quotation stage, each production unit connects its real quotation with random strings and performs hash encryption, because the hash function is easy to check and cannot be solved reversibly. The encrypted hash value is used as the sealed quotation and submitted before the deadline. This approach keeps the quotation unique and confidential. To prevent malignant competition, a certain amount of virtual currency should be transferred to the smart contract address as the deposit.

Definition 1: The hash function $hash: D \rightarrow R$ represents the mapping from D to R. Let $d = |D|$ and $r = |R|$ be the size of the definition domain and the value domain, respectively. Then, $d >> r$, i.e. the value range of the definition domain is much larger than that of the value domain. Thus, the has function is a "many-to-one" mapping that maps information of random sizes into a uniform size hash value.

According to Definition 1, the quotation sealing function can be determined as:

$$H = hash(t, a) \tag{6}$$

where, H is the sealed quotation; $hash(\bullet)$ is a hash function; t is the real quotation; a is a random string. The security of the hash-based quotation sealing function is demonstrated as follows: (1) the $hash(t, a)$ can be computed easily for any given t and a; (2) it is infeasible to find $hash(t, a) = H$ for any given H, due to the unidirectional nature of the hash function; (3) it is infeasible to find t' and a' such that $hash(t, a) = hash(t', a')$ for any given t and a, due to the weak collision resistance of the hash function; (4) it is infeasible to find any pair of (t, a) and (t', a') such that $hash(t, a) = hash(t', a')$, due to the strong collision resistance of the hash function. According to the principle of cryptography, the quotation sealing function enjoys excellent security.

In the CQTP phase, each production unit needs to submit the real quotation and the random string before the deadline of the public quotation. Then, the smart contract will check whether the hash function value $hash(t, a)$ equals the sealed quotation H submitted in the previous stage. If not, the quotation will be discarded; otherwise, the clearing queue and transaction price will be determined by the ERQ rule. If the new quotation is high than the highest quotation in the clearing queue and satisfies the capacity requirement, the next phase will be kicked off; otherwise, the clearing queue will be updated repeatedly until this phase is completed.

The security review is essential to any transaction. This phase mainly observes whether there is a physical unrealizable situation. This paper judges whether the adjustment power submitted by the transaction parties will exceed the transmission capacity limit of the corresponding line. If yes, adjustment should be made as per the method in Subsection 3.3 until the problem is solved. Once confirmed by the smart contract, the transaction volume and price of the two parties will be executed automatically and cannot be modified.

The transaction settlement is relatively simple. In this phase, the two parties execute the transaction in strict accordance with the price and volume determined in the previous phase, as well as the transaction settlement rules. After the transaction is completed, the deposits will be returned to the relevant parties.

4.3 Transaction settlement rules

Within the specified transaction period, all SDUs in the EPSDN involved in the transaction need to adjust their production and consumption plans, i.e. increasing the production or reducing the consumption, for the purpose of transaction [22, 23]. The transaction settlement platform observes the real-time production and consumption of each participant via smart meters, and makes settlement according to the specific situation.

Firstly, the deposits paid by all production units that fail to win the bid will be returned. Then, the settlement of the bid-winning production unit will be carried out in three cases.

Case 1: Supply-demand balance (the production unit can adjust the production and consumption plan according to the transaction result.)

This is the most desirable outcome. In this case, the settlement should be carried out at the price agreed between the production and consumption units, and the deposits should be returned to the relevant parties.

Case 2: Oversupply (the adjustment amount of the production unit exceeds the amount required for the transaction.)

In this case, the output of the backup unit should be reduced to maintain the balance between supply and demand. The two parties should settle at the agreed price and volume. Then, the production unit should receive a compensation for the backup unit:

$$C = \alpha \cdot p_{sb} \cdot \Delta Q \tag{7}$$

$$p_{sb} = p_{ge} - p_{ts} \tag{8}$$

where, C is the compensation amount; α is the compensation factor; p_{sb} is the cost of starting backup unit; ΔQ is the difference between the actual adjustment amount of the production unit and the amount required for the transaction; p_{ge} is the unit cost of power production; p_{ts} is the unit loss of the power transmission. Note that the value of α can be changed according to the transaction conditions, and is generally below 1.

Case 3: Short supply (the adjustment amount of the production unit fails to reach the amount required for the transaction.)

In this case, the output of the backup unit should be increase to maintain the balance between supply and demand. The two parties should settle at the agreed price and volume. Then, the production unit should be imposed a penalty for the backup unit:

$$D = \beta \cdot p_{sb} \cdot \Delta Q' \tag{9}$$

where, D is the penalty amount; β is the penalty factor; ΔQ is the difference between the actual adjustment amount of the production unit and the amount required for the transaction. Note that the value of β can be changed according to the transaction conditions, and is generally above 1.

5. Results and discussion: A case study

The proposed transaction mechanism was verified with an EPSDN containing 6 SDUs, denoted as SDUs A-F. The EPSDN structure is given is Fig. 7, where the nodes 3, 6, 7, 10, 13 and 15 correspond to the said SDUs. It is assumed that the day-ahead production plan has been determined, regardless of the participation of the standby unit. The remaining transmission capacity of each line in the distribution network is shown in Table 1.

In the simulation test, the SDUs in need of more power, i.e. consumption units, should initiate a request every 20 min according to their own demands. The request contains the power demand after 20 min. The production units should determine whether to accept the request within 1 min after the issuance. Then, quotation sealing, CQTP determination, security review, and settlement should be completed within 5 min, 10 min, 15 min and 20 min, respectively. After 20 min, the bid-winning production unit should supply the agreed amount of power to the consumption unit.

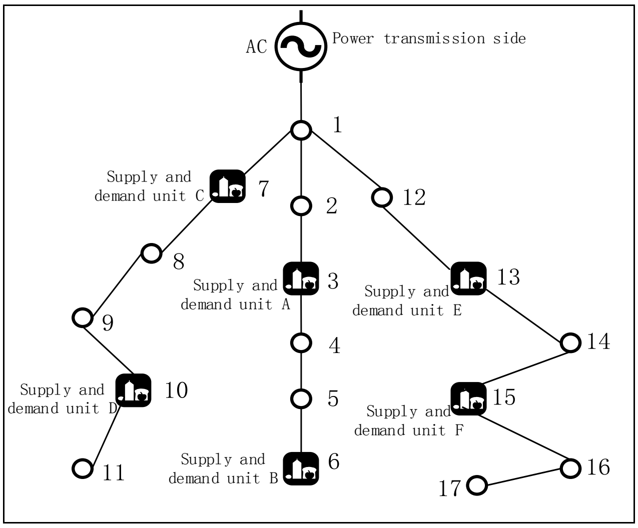

Fig. 7 The energy power supply and demand network (EPSDN) structure

Table 1 The remaining transmission capacity of each line in the distribution network

Branch node	Capacity remaining/kWh	Branch node	Capacity remaining/kWh
1-2	1.3	8-9	4.2
1-7	1.3	9-10	2.7
1-12	1.3	10-11	3.5
2-3	3.4	12-13	2.6
3-4	2.8	13-14	3.3
4-5	4.3	14-15	2.4
5-6	2.6	15-16	4.5
7-8	3.7	16-17	1.9

Before the simulation test, each SDU was given 5 units of virtual currency. The SDUs A, B and C were regarded as consumption units that send transaction requests to the system, while the SDUs D, E and F were considered as production units with adjustment ability that respond to the system requests. Ten transactions were simulated to fully verify the efficiency of the blockchain-based smart contract trading mechanism. Tables 2-4 respectively list the sealed quotation, real quotation and random string of each bidding production unit, the remaining capacity of each line before and after the security review, and the results of smart contract transaction. Fig. 8 provides the scatter plot on the transaction results.

Table 2 Sealed quotation, real quotation and random string

Stage	1	2	3	4	5	6	7	8	9	10
Sealed offer	Qwn123njdeijsw3wde	wid234mmj832fguQDc	QDFcgh459oh90db45d	Dgknvhr47jfi8SDvbn	DFced-mkfj7364mkddc	Xcdjsgfb84DCkch987	ckdjCK-JHldkDC76cjf	Cdfjsjnvlai47hdfj9fghj	hdk-cASD23kf34kdkfd	dfdkshDF675djfhdhc
Real offer(Virtual currency/kWh)	1.2	1.5	1.9	2.3	2.7	3	3.5	3.8	4.2	4.9
Random string	bgh	xdr	dfg	knb	okm	lkj	gfd	esz	ygv	fer

Table 3 The remaining capacity of each line before and after the security review

Stage	1		2		3		4		5		6		7		8		9		10	
Line	1-2	1-7	2-3	8-9	9-10	3-4	1-12	7-8	10-11	15-16	16-17	3-4	8-9	5-6	4-5	10-11	12-13	13-14	1-7	7-8
Remaining branch capacity before safety audit/kWh	1.3	1.3	3.4	4.2	2.7	2.8	1.3	3.7	3.5	4.5	1.9	2.8	4.2	2.6	4.3	3.5	2.6	3.3	1.3	3.7
Remaining branch capacity after safety audit/kWh	2.0	2.5	3.4	4.2	3.0	3.5	2.3	3.7	3.5	4.5	3.1	3.7	4.2	2.9	5.0	3.5	3.8	3.3	3.6	4.0

Table 4 The results of smart contract transaction

Stage	Total demand for consumer units/kWh	Supply and demand unit transaction price (Virtual currency/kWh)	Production unit of transaction	Volume (kWh)	Transaction revenue (Virtual currency)
1	0.8	1.582	D	0.2	0.3164
			E	0.6	0.9492
2	0.9	1.734	D	0.4	0.6936
			F	0.5	0.8670
3	0.3	2.012	E	0.2	0.4024
			F	0.1	0.2012
4	1.2	2.462	D	0.2	0.4924
			E	0.6	1.4772
			F	0.4	0.9848
5	0.7	2.813	D	0.3	0.8439
			F	0.4	1.1252
6	1.0	3.272	D	0.3	0.9816
			E	0.7	2.2904
7	0.5	3.657	E	0.4	1.4628
			F	0.1	0.3657
8	0.1	3.923	E	0.1	0.3923
9	0.6	4.502	D	0.3	1.3506
			F	0.3	1.3506
10	1.1	5.216	E	0.6	3.1296
			F	0.5	2.6080

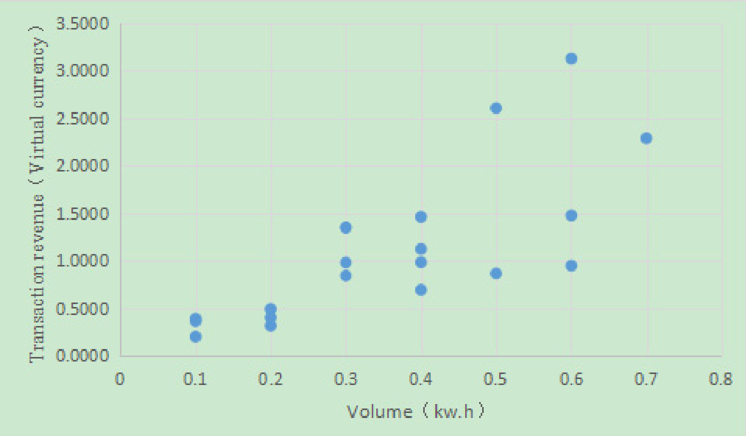

Fig. 8 The scatter plot on the transaction results

The results show that the three production units submitted the quotation sealing functions within the specified time, converting real quotes into random strings of the same length to ensure fair and secure transactions. Determined the clearing queue and price through the intelligent contract-based ERQ rule, once the parties have reached an agreement, they will immediately follow the agreement to prevent transaction friction. It can be seen from Table 3 that after the security review, the remaining capacity of each branch has undergone a certain change, which illustrates the necessity of the security review and prevents the situation from exceeding the capacity limit.

According to the final results of the 10 tests, the SDU D and the SDU E provided 0.8 kWh power to the consumption units in test 1, and respectively earned 0.3164 and 0.9492 units of virtual currently; the SDU E and the SDU F provided 0.3 kWh power to the consumption units in test 3, and respectively earned 0.4024 and 0.2012 units of virtual currently; the SDU D and the SDU F provided 0.7 kWh power to the consumption units in test 5, and respectively earned 0.8439 and 1.1252 units of virtual currently. The SDU E and the SDU F provided 0.5 kWh power to the consumption units in test 7, and respectively earned 1.4628 and 0.3657 units of virtual currently. the SDU D and the SDU F provided 0.6 kWh power to the consumption units in test 9, and respectively earned 1.3506 and 1.3506 units of virtual currently. In general, the SDUs in the network completed the targets in a secure and efficient manner: the SDUs A, B and C fulfilled their power demands, while the SDUs D, E and F respectively received 4.6785, 10.1039 and 7.5025 units of virtual currency. The scatter plot on the transaction results clearly displays that the transaction revenue basically increased with the power amount of the transaction, except for some singularities (i.e. the points with low power amount and high revenue). The trend reveals the importance of the quotation sealing of the production units, and that correct quotation can lead to better revenue.

6. Conclusion

In DG-dominated distribution networks, the traditional transaction method is prone to malicious attacks, which threatens the transaction security, and troubled by high transaction cost and poor transparency. To solve these problems, this paper sets up a point-to-point, secure and efficient trading system based on blockchain and smart contract. Firstly, the ERQ rule was adopted to maximize the revenue of the power trading market under the constraints on power difference, upper and lower bounds of for-sale power provided by production units, and the line transmission capacity, yielding a clearing queue and transaction price. On this basis, the author detailed the specific steps and implementation of the efficient power trading system. Considering the complexity of point-to-point transactions, the transaction was divided into six phases based on blockchain smart contract, namely, request issuance, request acceptance, quotation sealing, the CQTS determination, security review and settlement, aiming to ensure the safe and efficient operation of transactions in the distribution network. Through example analysis, the proposed method was proved capable of improving the transaction security and transparency in small-scale power markets involving numerous traders. Using the method proposed in this paper can help large and medium-sized enterprises to sell excess electricity or purchase the lack of electricity, maintain the balance of electricity consumption, thereby improving the economic efficiency of enterprises.

There are many other areas worth exploring for the integration between blockchain and energy trading, such as security and economic analysis on blockchain-based energy trading (i.e. optimizing the security and cost efficiency of energy trading in a decentralized and trust-free blockchain environment) and the construction of smart contract trading system for the fully open power market. Hence, the future research will establish optimization models for the cost efficiency of power transactions under the blockchain-based energy trading system, trying to further promote the application of our trading mechanism.

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Appendix A

Used abbreviations:

EPSDN	Energy power supply and demand network
ERQ	Encourage-real-quotation
SDU	Supply and demand unit
DG	Distributed generation
CQTP	Clearing queue and transaction price