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Electric Vehicle Power Trading Mechanism Based on Blockchain and Smart Contract in V2G Network

HAIQING LIU, YAN ZHANG, SHIQIANG ZHENG, AND YUANCHENG LI
School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China

Corresponding author: Yuancheng Li (ycli@ncepu.edu.cn)

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ABSTRACT In order to realize peer-to-peer (P2P) transactions between electric vehicles (EVs) in vehicle-to-grid (V2G) networks, we propose an EV power trading model based on blockchain and smart contract. Firstly, based on the blockchain and smart contract technology, a decentralized power trading model is proposed to realize the information equivalence and transparent openness of power trading. Then, considering the randomness and uncertainty of EV charging and discharging, the EV trading parties use the reverse auction mechanism based on dynamic pricing strategy to complete the transaction matching, which can not only improve the profit of the less competitive power seller, but also it can reduce the cost of the electricity purchaser. Finally, in order to verify the feasibility of our proposed scheme, V2G's EV power trading smart contract was designed, and the smart contract was released to Ethereum and simulated experiments were carried out. The effectiveness of the proposed scheme is verified by simulation experiments and comparison with traditional power trading schemes.

INDEX TERMS Blockchain, decentralization, reverse auctions, smart contract, V2G.

I. INTRODUCTION

With the advancement of various technologies in electric vehicles(EVs), the number of EVs and charging stations continues to climb, and a large number of independently decided EV users participate in electrical trading. Compared with traditional cars, EVs have obvious advantages in environmental protection and energy saving [1]. EVs can buy electricity at low valley, and sell electricity at peak times, so that achieving the role of "shaving peaks and eliminating valleys" [2]. It is extremely important to design an effective EV trading mechanism in V2G network research.

Traditional centralized electrical trading relies on trusted third parties, and there are problems such as single point of failure and privacy leakage [3]–[5]. Therefore, it is important to design a safe, efficient, transparent, information-symmetrical trading model and trading method. Recently, a promising blockchain technology with advantages of decentralization, security, and trust has been introduced for electricity trading. Satoshi Nakamoto [6] proposed the blockchain in 2008 and successfully applied it to the financial sector. Blockchain technology collectively maintains a reliable distributed database in a decentralized and de-trusted manner, eliminating the need for trusted third parties to address the high cost, inefficiency, and insecure data storage of traditional centralized organizations. Blockchain provides protection for EVs power centering transactions in V2G, which enables electricity trading to be executed in decentralized, transparent, and secure market environments [7]. It is very important to establish reliable, autonomous and automatic power trading between EVs by using blockchain and smart contract in V2G. It greatly improves energy efficiency, reduces management costs, and achieves efficient operation of the energy Internet.

Blockchain distributed power trading has attracted widespread attention from scholars. In a parking lot or charging station, EVs with bidirectional chargers can trade electricity in a localized peer-to-peer (P2P) manner (e.g., vehicle-to-vehicle) [8], [9]. Gai *et al.* [10] proposed a privacy-preserving based on consortium blockchain energy trading model in smart grid. However, the main research issue is using blockchain to protect the privacy of energy transactions, which does not participate in the trading process. To solve the security settlement problem brought by

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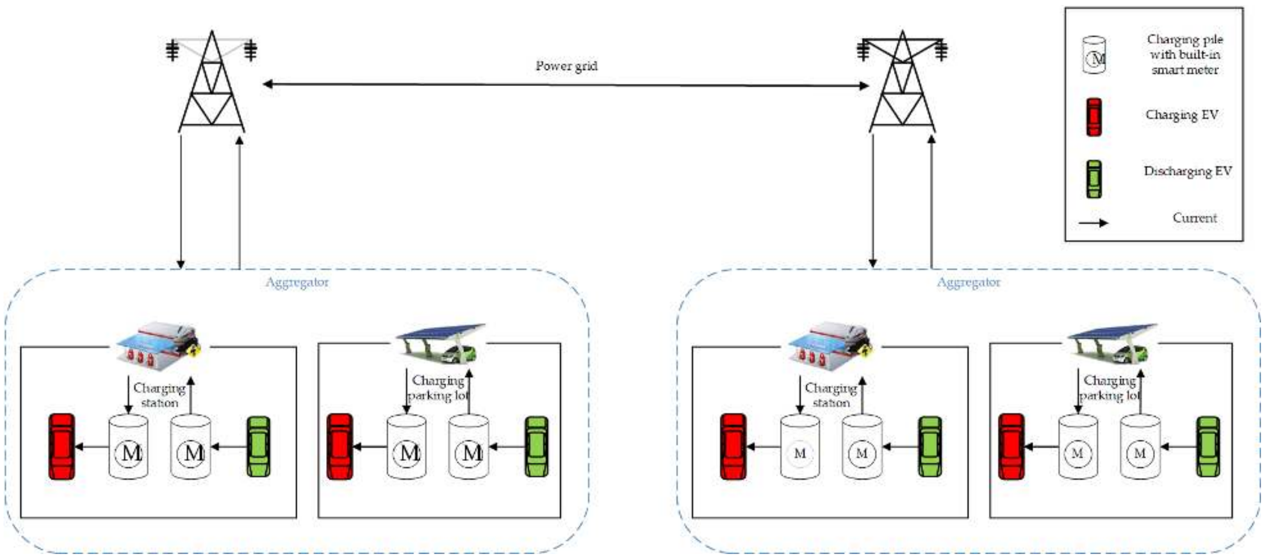

FIGURE 1. Decentralized network architecture in V2G.

distributed energy transaction, theoretical research on decentralized power trading based on blockchain technology in energy Internet was introduced [11]. Luo *et al.* [12] proposed a power transaction architecture based on multi-agent alliance (MAS), which use blockchain as the contract settlement system. In [13], a new hybrid blockchain storaging mode was designed. Anish *et al.* [14] proposed a blockchain based edge-as-a-service framework for secure energy trading in software defined networking (SDN)-enabled V2G environment. The scheme based on blockchain consensus mechanism that ensure the safety of the distributed energy trading. Yu *et al.* [15] proposed a blockchain-based P2P energy transaction model to provide distributed solutions for energy trading. However, the power transactions in the energy Internet proposed in [12]–[15] does not involve the power transaction of EVs. In [16], a localized P2P power trading model for local power trading between plug-in hybrid electric vehicles (PHEVs) was proposed in smart grids. In addition, the electricity price and trading power of PHEVs are solved by an iterative double auction mechanism. However, the power grid participation is not considered [16]. A blockchain-based secure energy transaction method uses SDN as the underlying architecture to reduce communication and computational overhead of network resources [17].

Motivated by these developments, we exploit the blockchain technology to develop a secure P2P electricity trading system. We introduce smart contract into V2G power trading, designs V2G EV trading smart contract, build a practical V2G power trading platform, and realizes P2P electric energy trading of EVs in V2G networks. The decentralized transaction model solves the problem of low efficiency and high market influence of the trading center, and the Pareto improvement is realized through system self-balancing. Blockchain technology makes decentralized energy trading without relying on a trusted third party, which ensure fairness, transparency and non-discrimination. Moreover, since electricity pricing along with the amount of traded electricity among EVs need to be optimized, an reverse auction mechanism is presented to maximize social welfare in the system. In order to verify the effectiveness of the proposed scheme and the optimality of the mechanism, we test the designed smart contract on the Ethereum private chain and conducts simulation experiments.

The primary contribution of the paper can be summarized as follows:

1) We establish a private blockchain based on aggregators to audit and verify transaction records among EVs.

2) We design a localized P2P electricity trading model with private blockchain to achieve trustful and secure electricity trading.

3) To optimize electricity pricing and the amount of traded electricity among EVs, a reverse auction mechanism is proposed to maximize social welfare while protecting privacy of EVs.

The rest of this paper is organized as follows. We introduce the decentralized power trading model in Section II. Decentralized trading rules based on reverse auctions are elaborated in Section III. In Section IV, we verify the validity of the smart contract through experiments. We summarize our work in Section V.

II. DECENTRALIZED TRADING MODEL

A. DECENTRALIZED NETWORK ARCHITECTURE IN V2G

In the V2G network in which EVs participate, the purchase demand and electric energy reserves of EVs have strong randomness and volatility, so flexible mechanisms are needed to achieve real-time balance between supply and demand.

Figure 1 shows the decentralized V2G architecture we designed. After all the charging EVs submit their own demand information to the smart grid, the aggregator sends the demand information to the discharging EVs. Then, the discharging EVs return their own energy information to

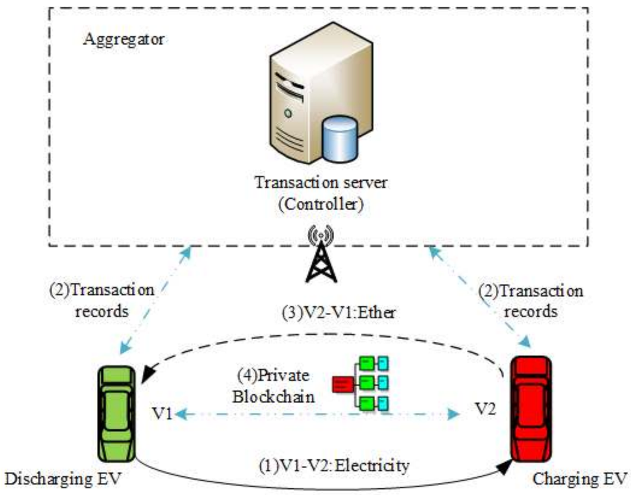

FIGURE 2. P2P electricity trading using ether in V2G.

the aggregator. Finally, the charging EVs and the discharging EVs complete the transaction with the participation of the aggregator, and the unfilled charging EVs are powered by smart grid.

Figure 2 shows the P2P electricity trading using ether in V2G we designed. EVs first select their own roles according to the electricity demand and energy status. Charging EVs request energy from discharging EVs, energy bidding and trading through a reverse auction mechanism. After that, the charging EVs pay ether to the discharging EVs.

EV power trading in V2G include the following entities:

1) ELECTRIC VEHICLES

EVs play different roles in V2G power trading, including charging EVs, discharging EVs and idle EVs. According to the current state of energy and drive plan, each EV chooses their own role.

2) AGGREGATOR

As an energy broker, aggregators provide power and wireless communication service access points for EVs. Charging EVs send requests for power demand to the nearest aggregator. Aggregators count local electricity demand and announce this demand to local EVs. EVs with surplus power supply prices to aggregators. As an auctioneer, aggregators conduct reverse auctions in EV transactions to complete the matching of EVs' electricity transactions.

3) SMART METER

Each charging post with a built-in smart meter calculates and records real-time trading power. The charging EV pays to the discharging EV according to the record in the smart meter.

4) POWER COMPANY

Power companies provide electricity and electricity sales services for EVs.

5) ETHER

The currency is used by EVs to trade with the grid or other EVs.

6) CHARGING PILE

Blockchain node.

B. SECURITY CONSTRAINTS

There is a dynamic balance between the distributed power supply and EVs. The decentralized trading mechanism allows for flexible trading between EVs, and eliminate the deviation between the actual power supply (or load) of the distributed power supplier and the EV and the power generation plan. Finally, the balance of the power flow the distribution network is realized.

Restrictions:

(1) Distribution network flow equation

$$\begin{cases} \Delta P = P_i - U_i \sum_{j=1}^{N_b} U_j(G_{ij}cos\delta_{ij} + B_{ij}sin\delta_{ij}) \\ \Delta Q = Q_i - U_i \sum_{j=1}^{N_b} U_j(G_{ij}sin\delta_{ij} + B_{ij}cos\delta_{ij}) \end{cases} \tag{1}$$

where: there are N_b nodes in the distribution network, ΔP_i is active power unbalance of the i-th node, ΔQ_i is reactive power unbalance of the i-th node; U_i is voltage amplitude, P_i is active power, Q_i is reactive power; G_{ij} is the conductance of the branch between nodes i and j, B_{ij} the susceptance of the branch between nodes i and j, δ_{ij} is the phase angle difference between branches between nodes i and j.

(2) Branch flow constraint

$$\begin{cases} P_i^{min} \le P_i + \Delta P_i \le P_i^{max} \\ Q_i^{min} \le Q_i + \Delta Q_i \le Q_i^{max} \end{cases} \tag{2}$$

In equation (2), the active power and reactive power transmitted by each branch must satisfy the upper and lower bounds of its transmission power.

(3) Node voltage constraint

$$U_i^{min} \le U_i \le U_i^{max} \tag{3}$$

Because EVs may cause local power overload when charging at the same node, it is necessary to consider the voltage amplitude constraints of each node of the distribution network.

(4) EV charging and discharging constraint

$$N_i(t) \le N_i^{max} \tag{4}$$

In each node, the number of EVs controlled is always less than the number of dispatchable EVs.

C. BLOCKCHAIN TECHNOLOGY AND ETHEREUM SMART CONTRACT TECHNOLOGY

As an open, distributed ledger, blockchain can be permanent and verifiable manner to effectively record transactions between the parties, each block contains a cryptographic hash of the previous block, a timestamp and transaction data (typically represented as a root hash MERKLE) [18]. The smart contract function is to allow trusted transactions to be executed without a third party [19]. These transactions are traceable and irreversible. The purpose of smart contract is to provide security that is superior to traditional contract law and to reduce other transaction costs associated with contracts. Smart contract is primarily used for general purpose computing purposes on blockchains or distributed ledgers.

Ethereum [20] is a distributed computing platform and operating system based on blockchain. It has a smart contract (script) function. It supports modified versions of the Nakamoto Consensus through transaction-based state transitions. Ethereum is written in the complete Turing language, including seven different programming languages. Developers use the language to create and publish applications that they know run inside Ethereum. In Ethereum, all smart contract is publicly stored on each node of the blockchain, which creates costs. As a blockchain, this means that Ethereum is safe by design and is an example of a distributed computing system with high Byzantine fault tolerance.

A complete P2P electricity trading among EVs has not yet been established. There is now a credible risk, mainly reflected in the fact that data such as transactions and settlements are stored in the grid center server, and the data is easily damaged during backup, storage, transmission, and transaction. At the same time, because of its storage mode and characteristics, it is vulnerable to attack and tampering, which reduces the credibility. Therefore, the use of blockchain technology multi-party collaboration, data traceability and immutability of blockchain, to improve the transparency and controllability of EVs in the entire process of trading, settlement and so on.

EV trading in V2G has problems such as opaque information, undisclosed rules, mutual trust in data and trading modes, inflexible power trading methods, large number of power transactions, unfixed trading hours, and large transaction amount randomness. Based on the blockchain to construct a decentralized power trading model, using blockchain technology multi-party cooperation, P2P communication, data traceability and immutability of blockchain, set up a good credit bridge for EV power trading, and realize EV power decentralization, traceability, transaction transparency, non-tamperable, P2P transactions, and refined and precise transaction management requirements in V2G.

At present, electronic contracts use digital certificates. This method is costly and inefficient, which seriously restricts the smooth development of EV power trading business in V2G. In the future, EVs will participate in more and more electric power transactions. The number of EVs may reach one million. If traditional digital certificates are still used, the cost of digital certificates will reach millions. We use the electronic signature of the blockchain-based identity voucher method to construct a low-cost legally valid blockchain electronic contract, which can greatly improve the efficiency of electronic contract circulation and reduce the cost of certificate construction and management.

Recently, the clearing and settlement process of electricity transactions are separate, and the grid adopts the monthly statement method of nissin. The clearing and settlement of trades need to be checked by people, which greatly reduces the trading efficiency and risks of mistakes. We use smart contract technology, after the completion of the transaction, according to the completion of the transaction and electronic contracts, will take the initiative to clear and settle, greatly improve the efficiency of the transaction, improve the credibility of the transaction.

The charging EV will release the electricity demand information on the blockchain, and the multiple discharging EVs with the demand information will write the response information and price on the block chain. Blockchain match charging EVs and discharging EVs automatically. After successful matching, sign the power contract. After the transaction, blockchain is settled according to the rules.

Because Ethereum has the characteristics of decentralization and Turing, it provides a good support for building V2G trading platform among EVs. We have designed a smart contract for EV power trading based on reverse auction. It serves as a core part of the EV power trading platform.

D. PROOF-OF-AUTHORITY

Proof-of-Authority (PoA) is a set of authorization nodes responsible for generating new blocks and block validation. Each privileged node continuously performs a hash calculation to find a block header whose hash value is smaller than a specific value, and the block header includes a PreHash, a local node address, a block sequence number, and a nonce. When the node finds the block header that satisfies the condition, it broadcasts the block header to network, and all nodes receive the broadcast for verification. If the verification passes, the block header in the broadcast is used as the data source, and N random nodes are randomly selected from the privileged nodes, and all the privileged nodes determine whether they are N random nodes. If you are one of the previous N-1 nodes, sign the block header with your private key, and broadcast the signature to network. If you are the Nth node, use this block header to construct a new block that contains as many transactions as possible during this period. The signature of the previous N-1 privileged node also has its own signature of the hash value of the complete blockchain. The complete block after this signature is then broadcast to network. All nodes are validated after receiving the complete block information. If verified, the block is considered to be a legal new block, and add it to the blockchain. If the block belongs to the longest chain, use it as the previous block and go back to the original step. Otherwise, it is discarded.

PoA has the following advantages: 1) Effectively alleviate the congestion problem of Ethereum, generate blocks every 5 seconds, and can process 1.5 million transactions per day; 2) No need to mine, improve transaction efficiency and reduce waste of computing resources; 3) Hard forks are legally bound and each Validator has a legal agreement.

1) BUILDING BLOCKS

The smart meters in the charging piles are ordinary nodes, and the aggregators are privileged nodes. Ordinary nodes only store their own related transaction records, and do not need to store all the data of the blockchain. Privileged nodes store all blockchain transactions. transaction during a certain period of time, this period of time block also needs to be stored.

Aggregators collect all local transaction records in a certain period, and then encrypt and digitally sign these records to guarantee authenticity and accuracy. The transaction records are structured into blocks. Each block contains a cryptographic hash to the prior block in the private blockchain. Whenever there is a transaction, it is sent to Authority, and it validates the transaction. The Validator in the POA network is the elected Authority. After the Validator validates and signs the transaction, the ordinary nodes synchronize the data from the Validator.

2) CARRYING OUT CONSENSUS PROCESS

The aggregator randomly selected to become a Validator of the current consensus process. The Validator broadcasts block data, timestamp, and its PoA to other authorized aggregators for verification and audit. These aggregators audit the block data and broadcast their audit results with their signatures to each other for mutual supervision and verification. All nodes are validated after receiving the complete block information. If the verification passes, the Validator will send records including current audited block data and a corresponding signature to all authorized aggregators for storage. After that, this block is stored in the private blockchain in a chronological order. Discard this block if the verification fails.

E. V2G ELECTRIC VEHICLE TRADING SMART CONTRACT

The EV trading smart contract should conform to the three principles, namely 1) Charging EVs and discharging EVs are voluntarily participating in the auction;2) Discharging EV quotes are classified as confidential during the auction period;3) Contract execution results are automatically settled.

This section divides electricity transactions into four phases in chronological order,quotes are classified as confidential including: submitting requirements, sealing quotes, publicly sealed quotes, and auction and transaction settlement. And we design the main function functions including submit demand function, sealed quotation function, open sealed quotation and auction function, transaction settlement function, etc. We use the electricity purchaser to purchase electricity as an example to illustrate the design method of smart contract. EV power trading process is shown in Figure 3.

1) SUBMIT DEMAND FUNCTION

Any purchaser in V2G can act as a publisher to submit a request for purchase of electricity on the trading platform

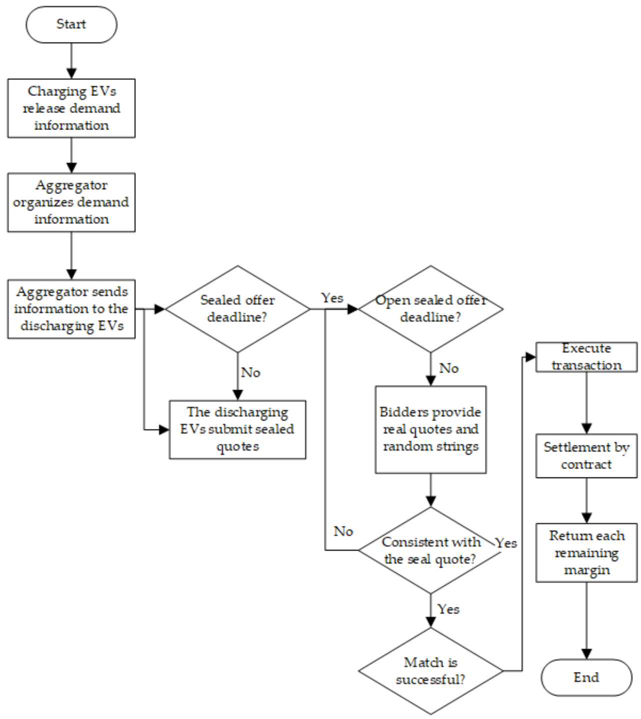

FIGURE 3. V2G electric vehicles based on transaction flow chart ethernet square.

during the submission of the demand phase. At the same time, a certain amount of Ethereum must be transferred to the smart contract address as a margin to avoid false requests. The smart contract logs all requests and sorts the requests by submission time.

2) SEALED QUOTATION FUNCTION

Since the information sent by the charging EV to the trading platform is visible to all, and the reverse auction is a sealed auction, that is, the discharging EV is required to submit the quotation and cannot know the quotation information of the remaining discharging EVs. We divide the bidding process into two steps: sealed quotes and open seal quotes. In the sealed quotation stage, the discharging EV uses a hash function that is irreversible and easy to verify, and connects its real quotation with a string of custom random strings, then hashes the cryptogram as a sealed quotation, which is submitted in the sealed quotation stage. This approach allows sealed-bid includes both real quote information is not tampered, leaked not to advance to the remaining discharging EVs. In addition, the discharging EV also needs to transfer certain Ethereum to the smart contract address as a margin to avoid malicious bidding. The value of the seal report is as shown in the (5).

$$H = S(v,s) \tag{5}$$

where: H is the sealed quote; $S(\cdot,\cdot)$ is the Secure Hash Algorithm 3 (SHA-3) hash function; v is the real quote; s is the random string customized by the power seller.

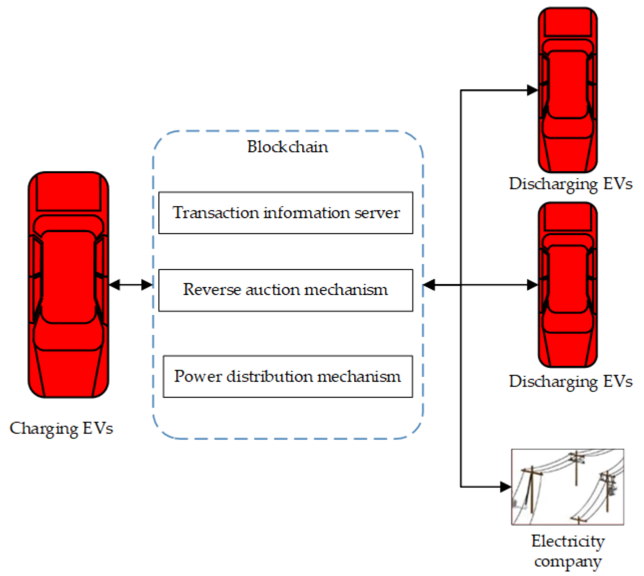

FIGURE 4. Reverse auction market model.

3) OPEN SEALED QUOTATION AND AUCTION FUNCTION

In the public seal quotation phase, the discharging EV needs to submit its own real quotation and a custom random string before the public seal quotation deadline. The smart contract verifies whether S (v, s) is consistent with the sealed quotation H submitted by the discharging EV. If not, the quotation has been considered invalid. Each time a smart contract receives a valid quote, it executes an auction function that is pre-approved by all members: the transaction price of each participant is recalculated according to the reverse auction rules until the end of the public offer period.

4) TRANSACTION SETTLEMENT FUNCTION

At the specified power transfer time, all participants in the power transaction trade as planned. The smart meters feedback the actual trading situation to the platform, and the platform settles according to the feedback data.

After all transactions are completed, it returns the remaining margin.

III. DECENTRALIZED TRADING RULES BASED ON REVERSE AUCTION

A. REVERSE AUCTION TRANSACTION MODEL

Transaction model is the basic research of EV transactions. In general, the EV power trading model is only for charging EVs, discharging EVs and power companies. At present, the allocation and distribution of China's power resources mainly adopts a static allocation mechanism, which makes electricity prices unable to adjust flexibly according to market changes. Compared with the traditional EV trading model, we proposed blockchain participation in the reverse auction trading model as shown in Figure 4.

In the reverse auction transaction model, the aggregator integrates the charging time period and the required cost, and finally selects the optimal solution. Before the auction begins, the charging EVs send their own demands to the aggregator, so that the aggregator can assign an optimal solution to it. The demand information of charging EVs includes: charging time period and charging amount.

When the aggregator receives the demand information sent by the charging EVs, it sorts out the demand information. Then, the aggregator forms a binary set $R_i(time_i, request_i)$ for each charging car demand information. $time_i$ indicates the charging period, $request_i$ indicates the amount of electricity demand. The aggregator then sends the formed binary set $R_i(time_i, request_i)$ to the discharge cars. When the discharging EVs receive the demand information, they send bid information to the aggregator according to all their power conditions. Finally, the aggregator evaluates all bidders participating in the auction and selects the highest score as the winner.

In the reverse auction transaction model, the main characteristics we consider for the electric energy of the discharging EVs are: sales time period, electric energy reserve, starting price of electric energy, and lowest selling price of electric energy. The discharging EVs describe the electrical energy in the form of a quad, i.e. $Bid_i(time_i$, amounti, fPricei, lPricei), $time_i$ indicates the period of power sales, $amount_i$ indicates electrical energy reserves, $fPrice_i$ indicates the starting price of electricity, $lPrice_i$ indicates the lowest selling price of electricity. When the discharging EVs receive the demand for electrical energy from the aggregator, they send them to the aggregator for bidding according to their power storage situation $Bid_i(time_i, amount_i, fPrice_i, lPrice_i)$.

B. REVERSE AUCTION TRANSACTION PROCESS

The study of the reverse auction transaction process can deepen the understanding of the reverse auction model, which refers to the links experienced by the two parties in the power exchange. Compared with the traditional power trading process, we proposed that the distribution plan of the power trading process and the price of electricity change as the transaction proceeds. On the one hand, it improves the efficiency of power trading by standardizing the description of power trading information; On the other hand, we study the end conditions of electricity trading.

In order to make electricity trading more efficient, charging EVs first send their own power demand information to the aggregator. The aggregator then sends the sorted demand information to discharge cars. Next, the discharging EVs send their own power information to the aggregator. Finally, the aggregator chooses the most suitable solution for power distribution. Specifically, as shown in Figure 5.

1. The users send their current power demand information to the aggregator, including the time period of purchase and the purchase price. At the time of auction, the users' auction order is determined according to the time period of purchase. If the users' power purchase period is the same, priority is given to the power distribution for users who purchase more power.

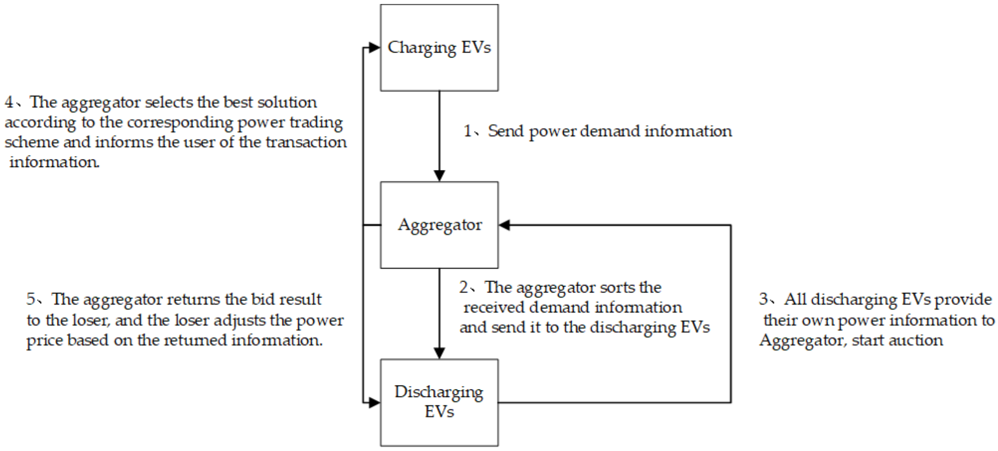

FIGURE 5. Reverse auction transaction process.

2. The aggregator sorts out after receiving the users' demand information. The aggregator organizes the demand information into a two-group form $R_i(time_i, request_i)$, timei indicates the charging period, and requesti indicates the amount of electricity purchased. Eventually, the aggregator sends the collated information to the discharging EVs.

3. After receiving the power demand information sent by the aggregator, the discharging EVs send their power information to the aggregator as $Bid_i(time_i, amount_i, fPrice_i, lPrice_i)$, $time_i$, represents the time period of power sales, $amount_i$ represents the amount of electricity stored, $fPrice_i$ represents the starting price of electricity, and $lPrice_i$ represents the lowest selling price of electricity.

4. After receiving the bidding information sent by the discharging EVs, the aggregator evaluates the users' demand information $R_i(time_i, request_i)$ and the bidding information $Bid_i(time_i, amount_i, fPrice_i, lPrice_i)$ sent by all the discharging EVs. The aggregator calculates the cost of each program, and finally chooses the least cost as the final winner. After the evaluation is completed, the aggregator notifies the user and the discharging car of the final result. The losers receive the lost auction information; the winner receives the information to win the auction and starts trading.

5. The discharging EVs lost in the auction adjust the price of electricity. If the adjusted electricity price is still higher than the lowest price lPrice, the new electricity price is the adjusted electricity price. Otherwise, the new electricity price is the lowest electricity price lPrice.

6. After each auction is completed, the next round of auctions is performed in the order specified in 1, and steps 2 through 5 above are repeated until all user transactions are completed.

After the blockchain selects the appropriate power distribution scheme, the payment step is entered, as is shown in Figure 6. Firstly, the blockchain judges whether there is false quotation and false quantity between the charging EVs and the discharging EVs. If one has this situation, the transaction fails, and blockchain pays the margin to the other. If this does not happen, the transaction continues, the discharging

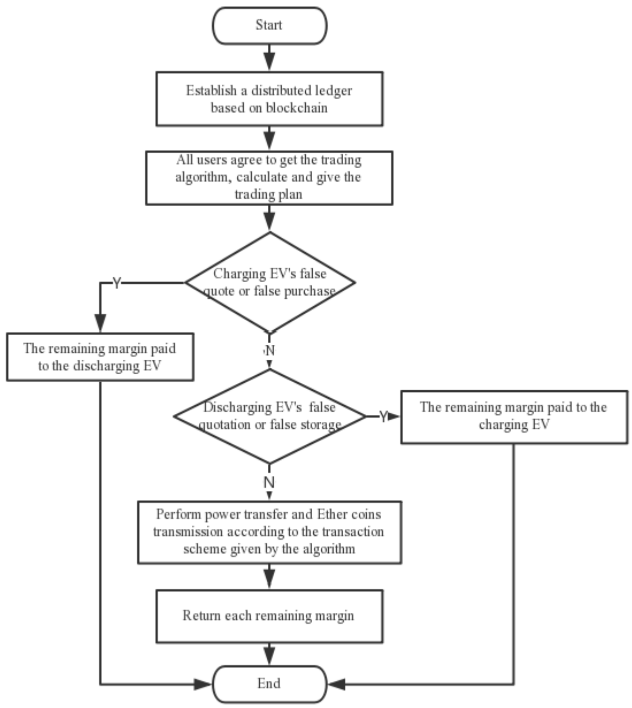

FIGURE 6. Reverse auction payment process.

EV transfers the electricity to the charging EV, the charging EV pays the discharging EV the ether, and the blockchain refunds the remaining deposit. The trading scheme and settlement result broad casting to network through the blockchain consensus mechanism, and the transaction information is recorded on the blockchain node.

C. PRICING STRATEGY IN REVERSE AUCTION

The traditional pricing strategy is mainly fixed price, that is, the price was determined in advance when the power was allocated, which makes the price of electricity not reflect the real situation of the market in real time. The reverse auction pricing strategy is using the theory of computational economics to adjust the balance of supply and demand of electricity prices. When at the peak of power consumption, it is adjusted by increasing the price of electricity; when in a low electricity valley, it is adjusted by lowering the electricity price. We dynamically determine the price of electricity based on the real state of the power resources: First determine the initial price of electricity, and then in each round of auction, the losers lower the price according to a certain percentage, which may increase the possibility of trading. Finally, in order to punish participants who provide false information, when the discharging EV fails to provide power as required, the final payment is reduced according to certain criteria.

The pricing strategy mainly involves the initial price of electricity, and the lowest price of electricity and the change strategy of electricity price. The initial price of electricity is the ''benchmark price + floating mechanism'' price negotiated with power generation enterprises. Agreed benchmark electricity price: both parties can independently negotiate and select a reasonable benchmark electricity price according to the power generation enterprise's power coal source, and determine the corresponding power generation price as the benchmark electricity price of the transaction contract. If the negotiation fails, the benchmark electricity price shall be determined by referring to the on-grid electricity price of coal benchmark or the power generation price corresponding to the long-term contract price of coal. Agreed floating mechanism: when signing a power market trading contract with power users in coal, steel, nonferrous metals, building materials and other industries and power generation enterprises, they may independently negotiate to establish a floating mechanism for the price, comprehensively consider various market influencing factors, and negotiate to determine the reference standard, floating period and floating proportion for the floating. If the negotiation fails, it is recommended to comprehensively consider the cost of power generation and various market factors, mainly referring to the market price of coal, taking into account the price of downstream products and other market factors, and implement a floating system, which can be adjusted once a quarter.

The price of electricity in the reverse auction is adjusted according to the transaction situation after the last round of auction. If the discharging EV A is the winner in the last round of auction, the electricity price remains unchanged. Otherwise, the price of the auction in this round is reduced according to a certain percentage, but the price cannot be lower than the pre-set minimum price.

Equation (6) shows the change in the price of electricity after each round of auction.

$$p_A^{cur'} = \begin{cases} p_A^{cur} & \text{if A is the winner} \\ p_A^{cur}.(1\text{-}r) & \text{if A is a loser and } p_A^{cur}.r > p_A^{rec} \\ p_A^{rec} & \text{if A is a loser and } p_A^{cur}.r < p_A^{rec} \end{cases} \quad (6)$$

$P_A^{cur'}$ is the adjusted electricity price, P_A^{cur} is the current electricity price, r is the rate of reduction in electricity prices, is the lowest price of electricity.

Here are two Lemma reverse auction pricing strategies to improve the competitiveness of weaker earnings discharging EVs and reduce the cost of charging EVs.

Lemma 1 the dynamic pricing strategy of reverse auction can increase the profit of the less competitive power seller.

Proof: It is assumed that power seller A and power seller B have the same conditions of power resources. The price of A is P_A, the price of B is P_B, and $P_A < P_B$. Therefore, the power seller A wins the auction, because its price is lower than the electricity price of the power seller B, which makes it more competitive. If the price of electricity is fixed, the competitiveness of power seller B is always weaker than that of power seller A, so that it cannot win any round of auction. If the price of electricity is dynamically changing, the seller of electricity B can reduce the price of the resource from P_B to P_B' until P_B' is lower than P_A. In this way, the electricity seller B can win the auction, thereby increasing the profit. Therefore, dynamic pricing strategies can increase the profitability of less competitive power sellers.

Lemma 2 the motivation pricing strategy can reduce the cost of the electricity purchaser.

It is assumed that power seller A and power seller B have the same conditions of power resources. The price of A is P_A, the price of B is P_B, and $P_A < P_B$. This way the user chooses the power seller A because its price is relatively low. If the price is fixed, the user always chooses the power seller A. However, if the price is dynamically changing, the power seller B lowers the price of the resource from P_B to P_B' in order to win the auction until P_B' is lower than P_A. Therefore, the user selects the power seller B and only pays P_B'. Therefore, dynamic pricing can reduce the cost of electricity buyers.

D. REVERSE AUCTION ALGORITHM BASED ON DYNAMIC PRICING

The winner is determined to be the core of power trading. The main research is how to allocate the most suitable power resources to the corresponding power purchasers, so that the overall social and economic benefits and resource utilization are optimal. The traditional power distribution scheme mainly uses a static allocation scheme, which cannot adapt to market changes. We mainly use the reverse auction method to make EVs compete for resources fairly by formulating some rules. First, all discharging EVs provide their own energy reserve information to the aggregator. The aggregator then selects from all of the discharging EVs that the constraints are met and the highest score is the winner. Our goal is to optimize social welfare and market efficiency through appropriate winner-determined programs.

The detailed steps of the reverse auction algorithm based on dynamic pricing are as follows:

1) The charging EVs submit the power demand information to the aggregator, which includes the time period of purchase and the purchase of electricity.
2) The aggregator processes the received user demand information and sends them to the discharging EVs.

Initiating an auction for each requirement in the order in which they are submitted. Moreover, each demand can only be carried out after the last demand auction is completed. For the demand initiated at the same time, the auction is initiated in the order of purchase power.

3) The discharging EVs send their relevant information to the aggregator for bidding according to own electric energy reserve situation. The information includes: the sales period of electric energy, the electric energy reserve, the starting sales price of electric energy and the lowest selling price of electric energy.
4) The aggregator calculates the different allocation schemes and the cost of each scheme according to the power information provided by all the participating discharging EVs. And it chooses the least expensive scheme and puts the discharging EV involved in the scheme into the winner of this round.
5) The aggregator sends the results of this round of auctions to the discharging EVs and the charging EVs.
6) For the winner, the price does not change. For the loser, it lowers its price to a certain extent, so that its final price is $P_A^{cur}(1-r)$, where P_A^{cur} is the price of the current round, and r is the rate of decrease. But when the price falls below its pre-set minimum price, the price remains at its stated minimum price.
7) Cycle through steps 2) through 6) in the order specified in 2 until all power purchase requirements have been auctioned. If the final power seller's power resources are all completed, the remaining power demand is provided by the grid.

Based on the pricing and trading matching of the reverse auction algorithm mentioned above, we designed the relevant smart contract. As a program on the blockchain of EV power trading, smart contract contains a series of EV power trading information including trading time, amount, buyer and seller, etc. Smart contract based on reverse auction algorithm as shown in Algorithm 1. The algorithm runs in the form of program script in the smart contract, which triggers the execution of the code through trading, and the trading information parameter is used as the parameter input value of the code, so the execution of the smart contract can realize the trading match.

The smart contract based on blockchain is the key to implement the application of blockchain technology. The development of specific applications is realized through the contents defined in the smart contract, such as state variables, struct types, functions, events, etc.

We define the information of buyers and sellers as the struct type in the blockchain smart contract, and the contents are as follows: (1) User information struct: struct Buyer, struct Seller; (2) Quote: float price; (3) Electricity: int amount; (4) Demand: int request.

The struct Buyer/Seller establishes transactions between EVs through mapping.

The time complexity of our proposed algorithm is $O(n^2)$.

Algorithm 1 Reverse Auction Algorithm

1: The buyer(charging EVs) quotation queue Rs is sorted according to the trading period $Rtime_i$, if the trading period is the same, it is sorted according to the demand $request_i$ from large to small, n is the total number of charging EVs queue.
2: $Rs = \{(Btime_1, request_1), \ldots (Rtime_n, request_n)\}$
3: The seller(discharging EVs) quotation queue Bids is sorted according to the start trading time $Btime_j$, $amount_j$ is the storage capacity, $fprice_j$ is the initial price, $lprice_j$ is the lowest price, m is the total number of discharging EVs queue.
4: $Bids = \{(Btime_1, amount_1, fprice_1, lprice_1), \ldots, (Btime_m, amount_m, fprice_m, lprice_m)\}$
5: Charging EVs and discharging EVs pay deposit to blockchain.
6: **while** Rs!={ } & Bids!={ } **do**
7: **for** $Btime_j \geq Btime_1$ **do**
8: Transaction price: $P = \min(fprice_1, \ldots, fprice_j)$
9: Seller winner: $Bid_{win} = (Btime_{win}, amount_{win}, fprice_{win}, lprice_{win})$
10: Volume of trade: $M = \min(request_1, amount_{win})$
11: A deal: P*M
12: Seller bid quantity update: $(Btime_{win}, amount_{win}, fprice_{win}, lprice_{win}) \leftarrow (Btime_{win}, amount_{win} - M, fprice_{win}, lprice_{win})$
13: Buyer bid quantity update: $(Btime_1, request_1) \leftarrow (Btime_1, request_1 - M)$
14: **if** $request_1 != 0$ **then**
15: goto 7
16: **else exit**
17: **end for**
18: **end while**
19: **for** $1 \leq k \leq j$ **do**
20: **if** $fprice_k > P$ & $fprice_k \times r > lprice_k$ **then**
21: $fprice_k \leftarrow fprice_k(1-r)$
22: **else** $fprice_k \leftarrow lprice_k$
23: **end for**
24: After each round of auctions, the next round of auctions in the order of the buyer queue, restart 6-23, until the charging EVs queue is empty.
25: Make records on blockchain according to returns

The miner will complete the following functions through the logical operation set by the smart contract: The purchase/sale quotation queue will match the transaction according to the reverse auction mechanism. EVs with successful matching will settle accounts and transfer, the settlement price is the price after the dynamic adjustment. Update queue parameters for matching and successfully trading Evs. Until the quotation queue of one of the buyer and the seller is all completed and cleared, the matching between the two parties stops.

We add safemath library, which is most commonly used in the blockchain industry development to prevent security problems such as numerical calculation overflow. Meanwhile, we use function modifiers to limit the operation permissions of related functions, prevent malicious calls and other security issues. With the further improvement and development of smart contract technology, our proposed electric vehicle trading method based on Ethereum smart contract will be improved and improved to achieve the coordination of safety and efficiency.

IV. SECURITY ANALYSIS AND NUMERICAL RESULTS

A. SECURITY ANALYSIS

Unlike traditional trading models, we use blockchain to ensure energy transaction security and privacy protection. The benefits gained by we designed blockchain-based scheme are as follows:

(1) Without reliance on the only trusted third party: EVs trade electricity in a P2P manner without a third party to make system robust and scalable.

(2) Privacy protection: Due to the reverse auction mechanism, EVs submit bid prices to the auctioneer without private information during trading, it is useful to protect identity privacy and account security.

(3) Transaction authentication: With the help of proof-of-authority, all transaction data is audited and authenticated by authorized aggregators.

(4) No double-spending: Energy coin relies on digital signatures to prove ownership and a public history of transactions to prevent double-spending.

B. NUMERICAL RESULTS

In order to explore the decentralized transaction method based on blockchain, we divide V2G multilateral transactions into five stages: release transaction, sealed quotation, open sealed quotation and auction, security check and transaction settlement. And we use Ethereum smart contract technology to design the V2G distributed multilateral trading smart contract, built a practical distributed multilateral trading platform for electric energy. We release the Ethereum private chain of EV power trading smart contract and conduct simulation experiments.

Assume that there are 5 charging EVs and 6 discharging EVs in the V2G network. The required power and transaction information of each car are shown in Table 1 and Table 2 below.

According to the above settings, the transaction price and transaction volume of the simulation experiment using MALTAB are shown in the following Figure 7. The transaction theory is 5 rounds and the transaction has completed 9 transactions. The order of completion of the transaction is as follows: [1, (2, 3)], [2, 6], [4, (3, 6, 1)], [5, 5], [3, (1, 5)]. As can be seen from Figure 7, the discharging EV 2, the discharging EV 3, the discharging EV 6, the discharging EV 5, and the discharging EV 1 complete the transaction. Since the initial price of the discharging EV 2 and the discharging EV 3 is relatively low, the transaction is completed first. The initial price of the discharge EV 1 is relatively high. Therefore, the previous bids failed. Because the price of electricity was dynamically adjusted, the transaction was successfully completed through several rounds of adjustment.

TABLE 1. Charging EVs information.

Type	Demand(Kw.h)	Trading period
Charging EV 1	80	7：00
Charging EV 2	50	7：15
Charging EV 3	60	8：00
Charging EV 4	70	7：20
Charging EV 5	40	7：30

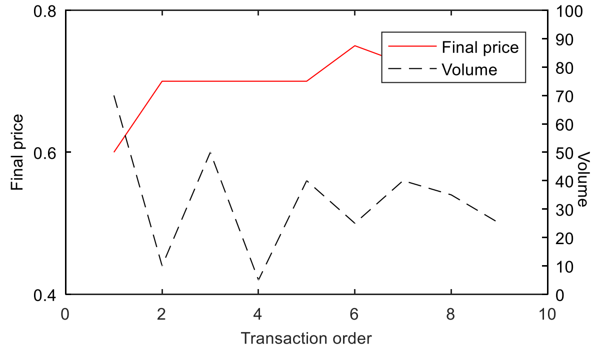

FIGURE 7. V2G transaction price and volume change curve.

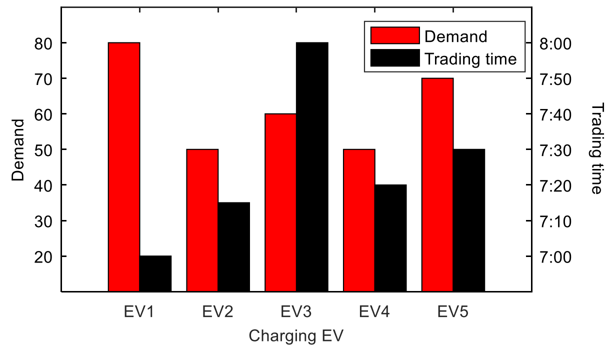

FIGURE 8. Charging EVs demand and trading time.

In power trading, the demand auction order of charging EVs is affected by demand and trading time. The bidding of the discharging EVs is affected by the quotation, storage and quotation time. Figure 8 shows the demand and transaction time of each charging EV. As can be seen from Figure 8, the charging EV 3 has the latest trading time, so the transaction is finally completed. Figure 9 shows the quotation and quotation time of each discharging EV. It can be seen from Figure 9 that although the quotation time of the discharging EV 1 is early, due to the high quotation, the first round failed to bid successfully. Since the bidding failed, the discharge EV 1 adjusted the quotation. In the subsequent rounds of auctions, the bidding still failed because the adjusted quotation was still higher than other users' quotations. In the third round, the bidding was successful because the other users had finished the quotation time. However, since the quotation is higher than the other two users, it is not possible

TABLE 2. Discharging EVs information.

Type	Storage capacity(Kw.)	Start trading time	Initial price	The lowest price
Discharging EV 1	60	6：00	0.8	0.5
Discharging EV 2	70	7：00	0.6	0.5
Discharging EV 3	50	7：00	0.7	0.5
Discharging EV 4	40	8：00	0.7	0.5
Discharging EV 5	80	7：00	0.8	0.5
Discharging EV 6	55	7：15	0.7	0.5
Power grid	-	-	0.85	0.5

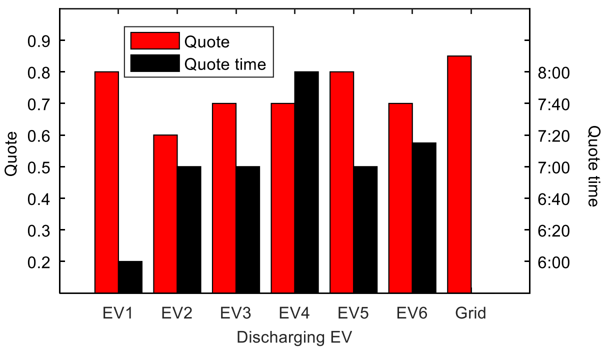

FIGURE 9. Discharging EVs quotation and quotation time.

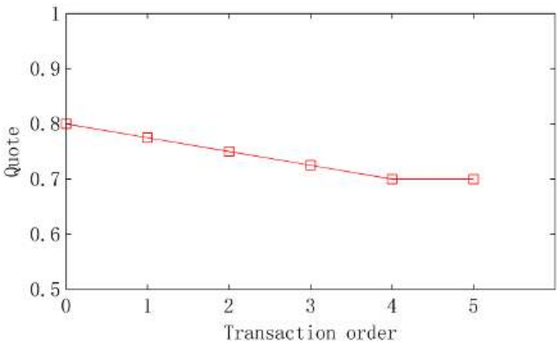

FIGURE 10. Discharging EV 1 quotation trend chart.

to participate in the transaction preferentially. In the last round of trading, although the quotations of the discharging EVs 1, 5 and 6 were the same, but the quotation time of the discharging EV 1 and the discharging EV 5 was earlier, the discharge EV 1 and the discharge EV 5 were successfully bid. The discharging EV 1 submits sealed quotes, real quotes and random strings as shown in Table 3. The discharging EV1 quotation adjustment chart is shown in Figure 10.

We compare the advantages and disadvantages of our scheme and traditional scheme [21] from social welfare [22] and market efficiency [23]. The comparison results are shown in Figures 11 and 12. Figure 11 shows that in 25 tests, the social welfare of our scheme was higher than traditional scheme. Since the electricity sellers in our scheme can adjust the quotations, and the traditional scheme is based on the blind auction, where the two parties cannot adjust the quotation according to the market changes, so the social welfare of our scheme is higher than the traditional scheme.

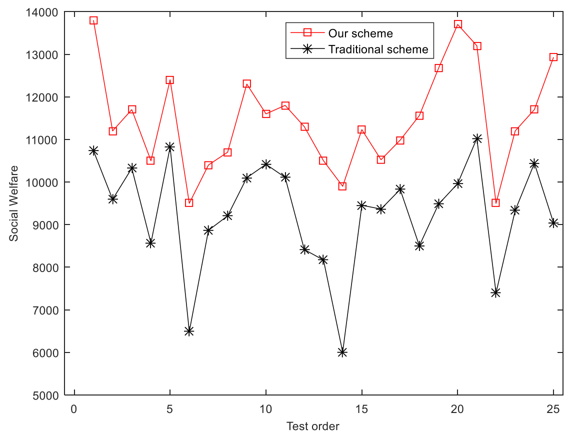

FIGURE 11. Social welfare test results chart.

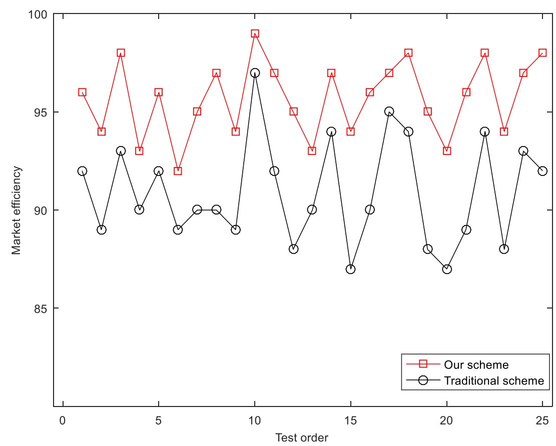

FIGURE 12. Market efficiency test results chart.

Market efficiency is calculated based on actual social welfare and maximum social welfare. It can be seen from Figure 12 that the market efficiency of our scheme is higher than the traditional scheme.

In order to verify the applicability and efficiency of our proposed scheme, we used more data for comparative experiments. By comparing the comparison of the two schemes in Figure 13, we can see that the success rate of participating transactions is higher when the number of EVs participating in the transaction is small, but with the increase of the number of EVs, the advantages of our proposed scheme are getting bigger and bigger. Our proposed scheme uses a

TABLE 3. Discharging EV1 sealed-bid.

Trading rounds	Sealed-bid	The real quote	Random string
1	"0x3dcb1e511413494ff8ef15f4g5fbd7344 13dcb1e520413494ff8ef05f4g5fbd7344"	0.8	"sdf
2	"0x29ce314b863e4dfbb51d8dg22b579b975 c2278c519f411g29c510g8278c8e99"	0.775	"xfd
3	"0x3610e4b745f9656gb6fc37d83ecd219cc 7c5be1877353:b683b7807c526e6611"	0.75	"ehg
4	"0x42b07g577373e4871b2259644gc594b39 234d1d7399bddbd131f45118796b6bc"	0.725	"qre
5	"0xf5d4017ecc916ff13fbd729d5f7cd55e5 4d6g88365e3b3ed2c8b79f936771b4e"	0.7	"gdh

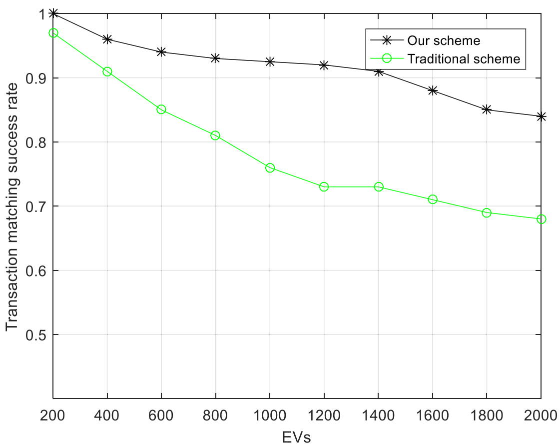

FIGURE 13. Different methods of trade matching success rate curve.

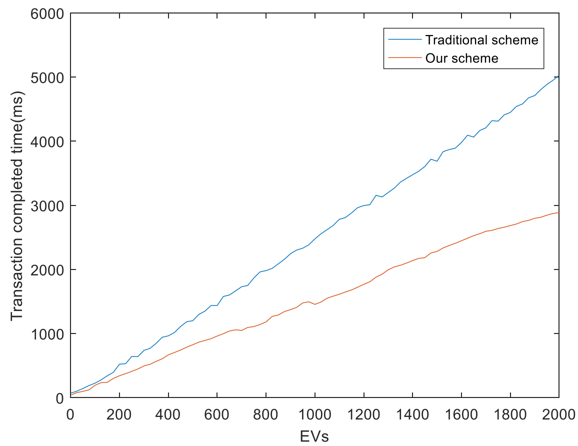

FIGURE 14. Different methods of efficiency curve.

reverse auction mechanism to achieve dynamic price adjustment. If the traditional scheme fails in one auction, it will be regarded as a transaction failure. As for our scheme, after a failure, the blockchain smart contract will dynamically adjust the price of the seller and improve the success rate of the transaction. Thus, the decentralized power trading algorithm based on reverse auction we proposed can improve the transaction success rate. As shown in Figure 14, when the number of EVs participating in the transaction is small, the time taken for the two schemes to complete the transaction is very close, but with the larger number of EVs participating in the transaction, the time gap between our scheme and the traditional scheme [21] to complete the transaction is gradually increasing. Traditional trading schemes cannot conduct P2P transactions with guaranteed security, it should be organized through the trading center. The blockchain can implement P2P transactions under the premise of ensuring security, no need for trading center participation. It can improve transaction efficiency, which is more obvious in actual power trading. In addition, our proposed scheme only carries out the consensus process on the preselected privileged nodes instead of all connected nodes in the blockchain. Moreover, we adopt POA consensus mechanism, no need to mine, the transaction speed is fast. The results indicate that our proposed scheme supports fast P2P energy trading.

The mechanism proposed by us is applicable to the situation of ''multi-transaction request and multi-response quotation'' for V2G transactions. On the other hand, it can ensure that all bidders' optimal quotation strategy is to declare their true cost of electricity generation and eliminate the game cost of producers and consumers. The results also show that under the reverse auction mechanism, both parties can dynamically adjust the quotation and have good adaptability to V2G power trading. As long as the parties to the transaction fulfill the trading contract, the mechanism designed by us can realize pareto improvement of all parties.

In addition, compared with the traditional power trading scheme, the proposed scheme is based on blockchain technology, so it does not rely on the transaction third party. In the traditional trading scheme, the transaction data is stored in the central server, and the transaction data is opaque and there is a risk of being forged. The blockchain solves the above problems through asymmetric cryptography, data signature and consensus mechanisms to ensure transaction data are transparent, non-tamper able and traceable.

V. CONCLUSION

In recent years, the rapid development of blockchain has facilitated the trading of EVs. We have studied how to build a decentralized transaction model in V2G based on blockchain technology. We used the reverse auction rules to design a decentralized EV power trading process. Then, based on the Ethereum blockchain technology, the EV power trading smart contract was designed and a practical trading platform was set up. The effectiveness of the proposed scheme is verified by simulation experiments and comparison with traditional power trading schemes. However, the blockchain research about EV power trading in V2G is still in its infancy, and further research is needed to make the blockchain technology truly land.

REFERENCES

[1] A. Mehrabi and K. Kim, "Low-complexity charging/discharging scheduling for electric vehicles at home and common lots for smart households prosumers," *IEEE Trans. Consum. Electron.*, vol. 64, no. 3, pp. 348–355, Aug. 2018.

[2] R. Alvaro-Hermana, J. Fraile-Ardanuy, D. Janssens, L. Knapen, and P. J. Zufiria, "Peer to peer energy trading with electric vehicles," *IEEE Intell. Transp. Syst. Mag.*, vol. 8, no. 3, pp. 33–44, Jul. 2016.

[3] X. Huang, Y. Zhang, D. Li, and L. Han, "An optimal scheduling algorithm for hybrid EV charging scenario using consortium blockchains," *Future Gener. Comput. Syst.*, vol. 91, pp. 555–562, Feb. 2019.

[4] N. Kumar, S. Misra, N. Chilamkurti, J. H. Lee, and J. J. P. C. Rodrigues, "Bayesian coalition negotiation game as a utility for secure energy management in a vehicles-to-grid environment," *IEEE Trans. Depend. Sec. Comput.*, vol. 13, no. 1, pp. 133–145, Jan. 2016.

[5] N. Z. Aitzhan and D. Svetinovic, "Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams," *IEEE Trans. Dependable Secure Comput.*, vol. 15, no. 5, pp. 840–852, Sep./Oct. 2016.

[6] S. Nakamoto, *Bitcoin: A Peer-to-Peer Electronic Cash System*. Accessed: Nov. 2008. [Online]. Available: https://bitco.in/pdf/bitcoin.pdf

[7] T. Salman, M. Zolanvari, A. Erbad, R. Jain, and M. Samaka, "Security services using blockchains: A state of the art survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1 pp. 858–880, Jan. 2018.

[8] C. Liu, K. K. Chai, X. Zhang, E. T. Lau, and Y. Chen, "Adaptive blockchain-based electric vehicle participation scheme in smart grid platform," *IEEE Access*, vol. 6, pp. 25657–25665, 2018.

[9] K. Zhang, Y. Mao, S. Leng, S. Maharjan, Y. Zhang, A. Vinel, and M. Jonsson, "Incentive-driven energy trading in the smart grid," *IEEE Access*, vol. 4, pp. 1243–1257, 2016.

[10] K. Gai, Y. Wu, L. Zhu, M. Qiu, and M. Shen, "Privacy-preserving energy trading using consortium blockchain in smart grid," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3548–3558, Jun. 2019.

[11] T. Yang, Q. Guo, H. Sun, B. Zhang, W. Zhao, C. Lin, and X. Tai, "Applying blockchain technology to decentralized operation in future energy internet," in *Proc. IEEE Conf. Energy Internet Energy System Integr.*, Beijing, China, Nov. 2017, pp. 1–5.

[12] F. Luo, Z. Y. Dong, J. Murata, Z. Xu, and G. Liang, "A distributed electricity trading system in active distribution networks based on multiagent coalition and blockchain," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 4097–4108, Sep. 2018.

[13] L. Wu, K. Meng, S. Li, M. Ding, Y. Suo, and S. Xu, "Democratic centralism: A hybrid blockchain architecture and its applications in energy Internet," in *Proc. IEEE Int. Conf. Energy Internet*, Beijing, China, Apr. 2017, pp. 176–181.

[14] J. Anish, A. G. Singh, and K. Neeraj, "SURVIVOR: A blockchain based edge-as-a-service framework for secure energy trading in SDN-enabled vehicle-to-grid environment," *Comput. Netw.*, vol. 153, pp. 36–48, Apr. 2019.

[15] Y. Yu, Y. Guo, and W. Min, "Trusted transactions in micro-grid based on blockchain," *Energies*, vol. 12, no. 10, p. 1952, May 2019.

[16] J. Kang, R. Yu, X. Huang, S. Maharjan, Y. Zhang, and E. Hossain, "Enabling localized peer-to-peer electricity trading among plug-in hybrid electric vehicles using consortium blockchains," *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 3154–3164, Dec. 2017.

[17] R. Chaudhary, A. Jindal, S. Aggarwal, N. Kumar, K.-K. R. Choo, and G. S. Aujla, "*BEST*: Blockchain-based secure energy trading in SDN-enabled intelligent transportation system," *Comput. Secur.*, vol. 85, pp. 288–299, Aug. 2019.

[18] E. Mengelkamp, B. Notheisen, C. Beer, D. Dauer, and C. Weinhardt, "A blockchain-based smart grid: Towards sustainable local energy markets," *Comput. Sci.-Res. Develop.*, vol. 33, nos. 1–2, pp. 207–214, 2018.

[19] A. Mavridou and A. Laszka, "Tool demonstration: FSolidM for designing secure Ethereum smart contracts," in *Proc. Int. Conf. Princ. Secur. Trust*, Thessaloniki, Greece, 2018, pp. 270–277.

[20] Z. C. Kennedy, D. E. Stephenson, J. F. Christ, T. R. Pope, C. A. Barrett, M. G. Warner, and B. W. Arey, "Enhanced anti-counterfeiting measures for additive manufacturing: Coupling lanthanide nanomaterial chemical signatures with blockchain technology," *J. Mater. Chem. C*, vol. 5, no. 37, pp. 9570–9578, 2017.

[21] J. Ma, J. Deng, L. Song, and Z. Han, "Incentive mechanism for demand side management in smart grid using auction," *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1379–1388, May 2014.

[22] T. Peng, Q. Xia, J. Jiang, and C. Kang, "Analysis of economic mechanism of two regional electricity market models," *Autom. Electric Power Syst.*, vol. 28, no. 7, pp. 20–23, Apr. 2004.

[23] J. Nicolaisen, V. Petrov, and L. Tesfatsion, "Market power and efficiency in a computational electricity market with discriminatory double-auction pricing," *IEEE Trans. Evol. Comput.*, vol. 5, no. 5, pp. 504–523, Oct. 2001.

HAIQING LIU received the Ph.D. degree in computer application technology from Wuhan University, in December 2001. She was a Visiting Scholar with the Worcester Polytechnics Institute (WPI), USA, in 2004. She transferred to the Control and Computer Engineering Academy, North China Electric Power University (NCEPU), in May 2005. She has been an Associate Professor and a Master's Supervisor with Wuhan University, since October 2002. She has been engaged in research and development work related to software engineering, database, and artificial intelligence, since 1988.

YAN ZHANG was born in Hebei, China, in 1995. She received the B.S. degree in computer science and technology from the Shanghai University of Electric Power, Shanghai, in 2018. She is currently pursuing the M.S. degree in computer technology with North China Electric Power University.

Her research interests include machine learning and artificial intelligence, blockchain, and electric vehicle in smart grid.

SHIQIANG ZHENG was born in Shanxi, China, in 1993. He received the B.S. degree in information security from North China Electric Power University, Beijing, in 2016, where he is currently pursuing the M.S. degree in computer science and technology.

His research interests include power market and blockchain, smart contact, and electric vehicle in smart grid.

YUANCHENG LI received the Ph.D. degree from the University of Science and Technology of China, Hefei, China, in 2003. From 2004 to 2005, he was a Postdoctoral Research Fellow with the Digital Media Laboratory, Beihang University, Beijing, China. From 2009 to 2010, he was a Postdoctoral Research Fellow with the Cyber Security Laboratory, College of Information Science and Technology, Pennsylvania State University, Pennsylvania, USA. Since 2005, he has been with North China Electric Power University, where he is currently a Professor and the Dean of the Institute of Smart Grid and Information Security.