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RESEARCH ARTICLE

Scheduling Management of Controllable Load Participating in Power Grid Enhanced by Double-Chain Structure

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ABSTRACT Smart grid has emerged as a successful application of cyber-physical systems in the electric power system. Among numerous key technologies of the smart grid, blockchain technology provides a promising solution to reduce the level of demand-side management by ensuring fair competition among all participating entities. However, it brings problems that it is difficult to balance decentralization and platform performance in the controllable scenario in the smart grid. In this paper, we propose a fair and efficient main/side chain framework by exploring the scalability of blockchain, integrating the operation of power entities, and building the decision-making model. First, we develop a main/side blockchain-based electric trading mechanism for controllable load. Then, we consider the operation and maintenance cost of power entities, and propose two decision-making model functions including controllable load and load agents. The optimization problem falls into the category of difference of convex programming and is solved by using the multi-objective evolutionary algorithm. Next, we propose the framework that the transaction process and power flow calculation process are deployed on the main chain and side chain respectively, which ensures the efficiency of the main chain. Finally, the performance of the proposed structure is validated via numerical results and theoretical analysis.

INDEX TERMS Double-chain blockchain, distributed trading, controllable load, network constraints, profit sharing.

I. INTRODUCTION

With the promotion of power system reform and the popularity of the concept of energy Internet, the intelligent power equipment including controllable load is gradually brought into the power grid to participate in the scheduling to alleviate the pressure of supply and demand [1]. In the diversified power market structure, some electricity selling companies transform into power agents that integrate demand resources and guide users to use electricity, and also become key decision-making subjects in the construction of energy Internet. The entry of such power entities will bring great uncertainty to the distribution network. If the long-term trading mode of real-time monthly settlement is still used, the resulting power deviation will bring huge dispatching cost to the power dispatching center. Therefore, to effectively utilize the flexible controllable load and protect the privacy of power users, the blockchain technology is used to build a new distributed transaction mechanism.

As a distributed database, the blockchain has advantages of equal rights of all nodes and transparent transaction information. It promotes all power entities to jointly maintain the sustainable development of the trading platform, so it has strong robustness [4]. The application of blockchain technology can directly realize the exchange of electricity purchase and sale information among all subjects in the distributed transaction mode, realize data transparency and reduce the uncertainty of the transaction. At the same time, the introduction of smart

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contract, as an automatic agreement processed by computers, provides a technical guarantee for the blockchain trading platform to improve the security and operation efficiency.

At present, some scholars have discussed the feasibility of applying blockchain technology in distributed power transaction. The unique features of the blockchain are transparency, tracking of end-to-end transaction, and the immutable information. For example, literature [5], [6] designed a distributed energy two-way auction protocol based on blockchain technology. In terms of demand-side resources, literature [7] designs a decentralized power transaction model with incentives to realize the flexible scheduling of demand-side resources. Literature [8] proposes an orderly charging strategy for electric vehicles (EVs) based on the characteristics of users' driving behavior, and schedules the charging behavior of EVs with the goal of minimizing the peak-cutting. In addition, literature [9] constructs the framework of distributed power transaction by discussing the similarity between the blockchain and microgrid power transaction.

For the specific scenario of optimal scheduling of controllable load into the power gird, some literatures mainly focus on maintaining the stable operation of the power grid and improving the comfort of users, proposing the double-layer scheduling with the characteristics of minimum reduction of air conditioning load and minimum start and stop [10], [11]. Some literatures mainly focus on clustering modeling of controllable load and improve the accuracy of controllable load scheduling in the form of dynamic scheduling [8], [12]. According to the platform on the block chain, some literatures establish the security mechanism of multi-level bidding transmission in an untrusted environment [13].

Although blockchain technology has shown immense potential in the power industry by securing and auditing P2P-based trasnactions of controllable load [14], [15], the above models are only simple applications of smart contracts, rarely involving the optimization of the underlying technology of blockchain for the distributed power trading platform with controllable load, and the realization of the deep integration of specific scenarios and blockchain. Existing blockchain platform is not applicable to the power trading scenario because of the high real-time requirements [16]. Meanwhile, the single-chain blockchain structure causes transaction information and power network data to be stored on a single chain, making the data complex and difficult to retrieve [17].

When there are multiple physical individuals in a power trading model, the single blockchain fails to meet the real-time requirements of power trading [18]. To address those challenges, some literatures have proposed double-chain structure in the economic optimization of the microgrid [19]. Literature [20] has prposed the basic concepts of blockchain cross-chain technology such as side chain and hash locking, which provide constructive help for our subsequent research on double-chain technology. Literature [21] and [22] has set the key goal of cross-chain technology to the transaction security, through the a multi-energy complementation and safety transaction model to facilitate the transaction subject's privacy security from leakage. On the basis of previous studies on double-chain technology, we find that the current blockchain technology will not be able to meet the needs of controllable load, a transaction subject with high real-time requirements. Therefore, the innovation of this paper is mainly reflected in the separate deployment of transaction chain and power chain to effectively improve the speed of accounting. At the same time, due to the diversity of trading subjects, the consensus algorithm is improved to improve the consensus efficiency. We propose a charge and discharge strategy for controllable load with P2P trading method based on double-chain blockchain structure. The strategy considers different interest demands as follows: controllable load users optimally participate in charging and discharging scheduling based on travel time and their own economic interests. Load agents not only need to consider their own economy, but also need to ensure the stability of the power load. The main contributions of this paper are threefold:

1) Double-chain blockchain: this paper refers to and improves the cross-chain technology in literature [20], and effectively improves the drawbacks of the existing power transaction blockchain platform. The double-chain structure blockchain proposed in this paper deploys transaction information and physical information separately. The electric energy chain adopts the multi-center alliance chain scheme to realize the security check of the trading scheme. The double-chain blockchain can effectively balance the two requirements of transaction cost reduction and peer-to-peer transaction security and trust.
2) Independent decision model: based on the different economic models of power users and load agents, the smart contract representation of two kinds of decision model functions is established in this paper. In order to realize the economic optimization of each power subject, the smooth operation of power load curve is also guaranteed.
3) Improvement of the underlying technology: in order to realize the long-term effective operation of the blockchain system, this paper optimizes and improves the underlying technology, and proposes to take the profit sharing of agents as the incentive mechanism and the rate of change of efficiency function as the consensus algorithm, which contributed to a more reasonable distribution of interests among agents.

The remainder of the paper is organized as follows. Section II presents the framework of the transaction mechanism of controllable load participating in the electricity market under the blockchain. While in section III, two smart contract decision-making models of power users and load agents are established based on the principle of benefit optimization based on the integration of power user operation characteristics. Section IV designs the cross-chain data structure of double-chain blockchain based on the notary

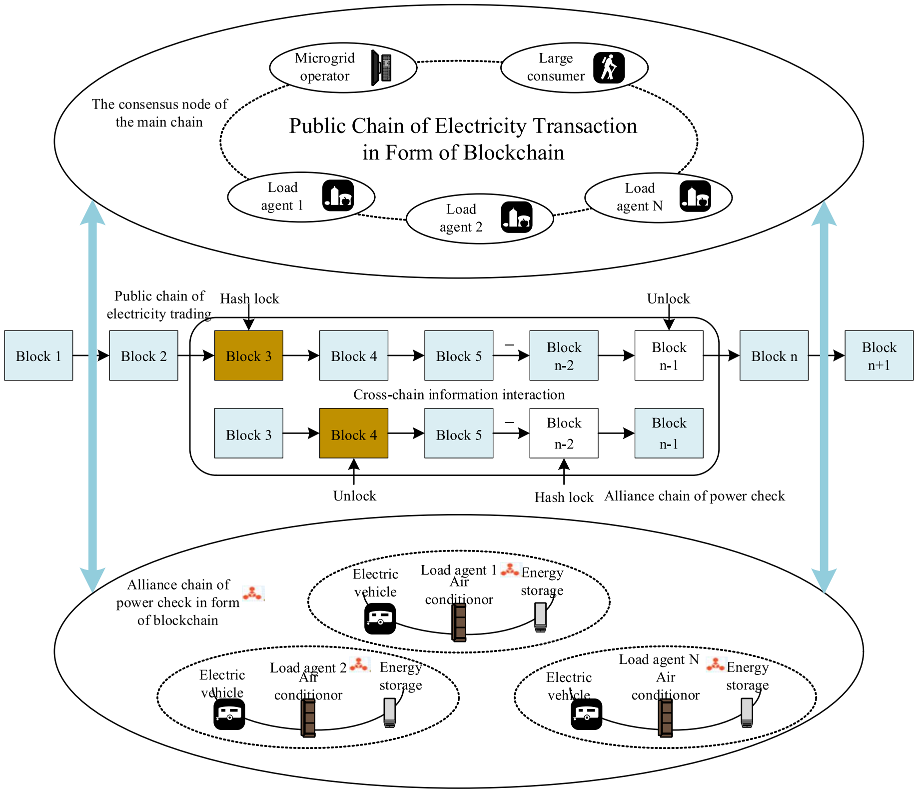


FIGURE 1. Framework of controllable load and load agent under blockchain technology.

mechanism, optimizes and improves the underlying technology, and proposes to take the profit sharing of agents as the incentive mechanism and the rate of change of efficiency function as the consensus algorithm to realize the multi-benefit win-win situation in the scenario of controllable load participating in power grid.

II. OVERVIEW of BLOCKCHAIN TRANSACTION FRAMEWORK

According to the current research on blockchain cross-chain technology, the P2P power trading is often combined with other trading chain, like carbon trading chain [23], information chain [24] and integrated energy market chain [25]. These studies make good use of blockchain technology to facilitate the combination of power trading and other trading platforms, but do not consider the complex physical operation state of power trading. Therefore, we propose the double-chain structure of controllable load participating in power grid scheduling mode is designed as shown in Figure 1.

At present, when power transactions are carried out on the single-chain block chain, each block not only needs to store the transaction information of each node, but also needs to store the power data of the whole system, resulting in the rapid increase of the block chain capacity and performance decline. In the proposed structure, the transaction information and physical information are deployed separately, and the transaction chain and the power chain are coupled and operate independently. The decentralized public chain is adopted in the transaction chain, which only stores the transaction information between each node and realizes the independent decision of all power users in the transaction scheme. In the power chain, a multi-center alliance chain is adopted to select trusted nodes in the system to participate in the chain security check, and the transaction deployment is adjusted, other nodes in the power chain verify the credibility and fairness of the transaction adjustment according to the block information, that is, only when most nodes verify and agree to the transaction adjustment implemented by the right node, the transaction adjustment block can be certified as valid. Therefore, the power chain constructed by multi-center or multi-node alliance chain avoids the monopoly of single node check. The secure interaction and trust mechanism of data between the transaction chain and the power chain follows the specific implementation of the cross-chain technology of the blockchain. The notary mechanism is adopted to realize the cross-chain. The cross-chain parties elect the node of verification right as the third party of mutual trust. In the cross-chain process, the block header information submitted by the right node must be verified, including the digital signature encrypted by public/private key technology and the merkle root. The legitimacy of the data source can be ensured by the digital signature, and the merkle root is used to verify the integrity of the transaction content, so communication security is ensured between the transaction chain and the power chain.

III. BLOCKCHAIN TRANSACTION MODEL IN CONTROLLABLE LOAD - AGENTS SCENARIO

Due to the diversity of power consumers with different energy demand, and the energy demand reflects the characteristics of electricity consumption behavior of users. If massive power consumers are controlled in sequence, it would bring huge computing difficulties to optimal dispatching. Therefore, it is important to cluster the controllable load according to the demand of power consumers. At the time, there are various types of intelligent electrical equipment on the demand side without loss of generality. Two representatives of electrical equipment on the demand side: EVs and air conditioners (ACs) are selected as the research objects for consideration.

The travel characteristics of large-scale power consumers have certain regularity, so the time when consumers return home in the evening and leave home in the morning determines the time when power consumers' duration of dispatching time. Therefore, the time when users going home and leaving home is considered as the clustering standard. Finally, users with similar electricity characteristics will be controlled by the same power agent, and large-scale charging and discharging resources will be integrated to participate in the conclusion of the above smart contract.

A. DECISION MODEL OF POWER CONSUMER

EV users purchase and sell electricity from the power grid through agents. Considering the cost of electricity purchase, battery loss cost and discharge benefits, the demand cost model of EVs is established as follows:

$$C_{\mathrm{ev}}(k) = C_{\mathrm{ev}}^{\mathrm{buy}}(k) + C_{\mathrm{ev}}^{\mathrm{loss}}(k) - C_{\mathrm{ev}}^{\mathrm{pro}}(k) \tag{1}$$

where, $C_{\mathrm{ev}}(k)$ is the demand cost model of EVs; $C_{\mathrm{ev}}^{\mathrm{buy}}(k)$ is the cost of electricity purchase; $C_{\mathrm{ev}}^{\mathrm{loss}}(k)$ is the battery loss cost, which represents the battery degradation cost caused by EVs participating in V2G; $C_{\mathrm{ev}}^{\mathrm{pro}}(k)$ is the discharge benefits.

The composition of each part is shown as follows:

$$\begin{cases} C_{\mathrm{ev}}^{\mathrm{buy}}(k) = \sum_{t=1}^{T}\sum_{i=1}^{N_k^{\mathrm{ev}}} P_{\mathrm{ch}}(i,t)\cdot\Delta t\cdot W_{\mathrm{ch}}(t), \\ x(i,t)=1 \\ C_{\mathrm{ev}}^{\mathrm{loss}}(k) = \sum_{t=1}^{T}\sum_{i=1}^{N_k^{\mathrm{ev}}} |P_{\mathrm{dch}}(i,t)|\cdot W_{\mathrm{loss}}(t), \\ p_{\mathrm{dch}}(i,t) = \begin{cases} P_{\mathrm{ch}}(i,t) & x(i,t)=1 \\ -P_{\mathrm{dc}}(i,t) & x(i,t)=-1 \end{cases} \\ C_{\mathrm{ev}}^{\mathrm{pro}}(k) = \sum_{t=1}^{T}\sum_{i=1}^{N_k^{\mathrm{ev}}} P_{\mathrm{dc}}(i,t)\cdot\Delta t\cdot W_{\mathrm{pro}}(t) \\ x(i,t)=-1 \end{cases} \tag{2}$$

where, T represents the scheduling time of one period, which is 96 in this paper; N_k^{ev} is the number of users owning EVs in the power user subgroup k after cluster; $P_{\mathrm{dch}}(i,t)$ is the charge and discharge power of EVs; $x(i,t)$ is the charging and discharging state of EVs in time period t, which -1 is the discharge, 1 is the charge and 0 is the idle state; $W_{\mathrm{ch}}(t)$ is the charging electricity price in time period t; $W_{\mathrm{loss}}(t)$ is the unit loss cost of power battery in the time period t; $W_{\mathrm{pro}}(t)$ is the discharge price in the time period t.

The constraint conditions of the user subgroup k are set as follows:

a. Constraint of travel:

$$S_{\mathrm{min}}^{\mathrm{SOC}} < S_{\mathrm{rea}}^{\mathrm{SOC}}(i) < S_{\mathrm{max}}^{\mathrm{SOC}} \tag{3}$$

where, the travel constraint is based on the state of charge (SOC) of EVs; $S_{\mathrm{rea}}^{\mathrm{SOC}}(i)$ is the actual travel demand of EVs; $S_{\mathrm{max}}^{\mathrm{SOC}}$ and $S_{\mathrm{min}}^{\mathrm{SOC}}$ are the maximum and minimum power demands of user for travel.

b. Constraint of charge and discharge:

$$x(i,t) = \begin{cases} 1, & \text{state of charge} \\ 0 & \text{idle state} \\ -1 & \text{state of discharge} \end{cases} \quad t\in[T_s(i), T_e(i)] \tag{4}$$

where, $T_s(i)$ and $T_e(i)$ are the homing and leaving time of the aggregated user subgroup respectively.

c. Constraint of battery capacity:

$$\begin{cases} S^{\mathrm{SOC}}(i,t) = S^{\mathrm{SOC}}(i,t-1) + P_{\mathrm{dch}}(i,t)\cdot\Delta t/B \\ S_{rea}^{\mathrm{SOC}}(i) \le S^{\mathrm{SOC}}(i, T_e(i)) \end{cases} \tag{5}$$

where, $S^{\mathrm{SOC}}(i,t)$ is the SOC of EVs at the end of time t; B is the battery capacity of EVs; Δt is the duration of one scheduling period.

For the ACs, assuming that there are ACs with similar thermal parameters and initial state in the user subgroup, the electricity cost of power users is expressed as follows:

$$C_{\mathrm{ac}}^{\mathrm{buy}}(k) = \sum_{t=1}^{24}\sum_{i=1}^{N_k^{\mathrm{AC}}} P_{\mathrm{ac}}(i,t)\cdot W_{\mathrm{ch}}(t) \tag{6}$$

where, $C_{\mathrm{ac}}^{\mathrm{buy}}(k)$ is the electricity cost of power users; $P_{\mathrm{ac}}(i,t)$ is the power consumption of the ACs corresponding to the time period t.

The agents can achieve the unification of electricity comfort and economy by appropriately adjusting the set temperature. The relationship between outdoor temperature, power of ACs and indoor temperature is expressed as follows:

$$\begin{aligned} T_{t+1}^{\mathrm{in}} &= \varepsilon^T T_t^{\mathrm{in}} \\ &\quad + (1-\varepsilon^T)(T_t^{\mathrm{out}} - 0.56\eta P_{\mathrm{ac}}(i,t)/A) \end{aligned} \tag{7}$$

where, T_t^{out} is the outdoor temperature; $P_{\mathrm{ac}}(i,t)$ is the power of ACs; T_t^{in} is the indoor temperature (in °C); ε^T is the inertia of the system; η is the efficiency coefficient; A is the coefficient of heat conduction.

The setting temperature constraints of the ACs are expressed as follows:

$$\left|T_{\mathrm{desired}} - T_t^{\mathrm{in}}\right| < \delta \tag{8}$$

where, T_{desired} is the most comfortable indoor temperature; δ is the range of indoor allowable temperature.

Considering electric vehicle and air conditioning load, the economic decision model of power users is calculated. Since the scenario where the agent acts as a third party to buy and sell electricity is considered, the power consumer also needs to pay commission fee to the agent. The decision model is shown as follows:

$$\begin{aligned} \min\ C_{\text{user}}(k) = {} & C_{\text{ev}}^{\text{buy}}(k) + C_{\text{ev}}^{\text{loss}}(k) \\ & - C_{\text{ev}}^{\text{pro}}(k) + C_{\text{ac}}^{\text{buy}}(k) + C_{\text{age}}(k) \end{aligned} \tag{9}$$

where, $C_{\text{user}}(k)$ is the economic cost function; $C_{\text{age}}(k)$ is the agent commission.

$C_{\text{age}}(k)$ is expressed as follows:

$$C_{\text{age}}(k) = N_k^{\text{ev}} \cdot W_{\text{age}}^{\text{ev}} + N_k^{\text{ac}} \cdot W_{\text{age}}^{\text{ac}} \tag{10}$$

where, $W_{\text{age}}^{\text{ev}}$ and $W_{\text{age}}^{\text{ac}}$ are fees for EVs and ACs.

B. DECISION MODEL OF LOAD AGENTS

The income of load agents comes from the designed blockchain distributed transaction system, so the load agent must assume the responsibility of system data maintenance and blockchain accounting. Therefore, when considering the decision model of the load agent, it is not only necessary to consider the optimal economic benefits, but also to maintain the operation of the entire system. The agent efficiency function can be established based on the above two indicators and used in the update of the consensus algorithm.

The economic decision-making model of load agents aims at the optimal economics of the agents, and the income from the sale of electricity is expressed as follows:

$$\begin{cases} E_{\text{sell}}^{\text{Agent}} = \displaystyle\sum_{t=1}^{24} \sum_{i=1}^{N_k^{\text{ev}}} P_{\text{dc}}(i,t) \cdot \Delta t \cdot W_{\text{dc}}(t), \\ x(i,t) = -1, t \in [T_s(i), T_e(i)] \end{cases} \tag{11}$$

where, $E_{\text{sell}}^{\text{Agent}}$ is the income from the sale of electricity; $W_{\text{dc}}(t)$ is the discharge income of agent.

Since the ACs don't involve discharging to the power grid, the main way of selling electricity for agents to the grid is the V2G of electric vehicles.

The revenue from the sales of electricity by agents also needs to exclude the revenue from the user's sales of electricity. In addition, since agents purchase electricity on behalf of consumers, they also need to extract corresponding agent fees. Therefore, the agent economic decision model integrating user subgroups is shown as follows:

$$\begin{aligned} \max\ E_{\text{Agent}}(k) = {} & E_{\text{sell}}^{\text{Agent}}(k) \\ & - C_{\text{ev}}^{\text{pro}}(k) + C_{\text{age}}(k) \end{aligned} \tag{12}$$

In the controllable load-load agents decentralized system, agents who assume full-node responsibilities realize the optimal allocation of power resources on the basis of balancing their economic benefits and power load curves. While ensuring its own economic interests, it provides a flexible solution strategy for grid load peak-cutting. The agent takes the minimum load variance as the objective function of the operation and maintenance model, and obtains:

$$\begin{aligned} \min\ V_{\text{Load}}(k) &= \frac{1}{24} \sum_{t=1}^{24} \Big(P_{\text{BL}}(t) + \sum_{i=1}^{N_k^{\text{ev}}} P_{\text{dch}}(i,t) \\ &\quad + \sum_{i=1}^{N_k^{\text{ac}}} P_{\text{ac}}(i,t) - P_{\text{av}}\Big)^2 \\ P_{\text{av}} &= \frac{1}{24} \sum_{t=1}^{24} \Big(P_{\text{BL}}(t) + \sum_{i=1}^{N_k^{\text{ev}}} P_{\text{dch}}(i,t) \\ &\quad + \sum_{i=1}^{N_k^{\text{ac}}} P_{\text{ac}}(i,t)\Big) \end{aligned} \tag{13}$$

where, $V_{\text{Load}}(k)$ is the load variance; $P_{\text{BL}}(t)$ is the electricity base load; P_{av} is the average power consumption load of power users during the whole period including EVs and ACs.

In conclusion, the decision model of the load agent is obtained as follows:

$$\begin{cases} \max E_{\text{agent}}(k) \\ \min V_{\text{Load}}(k) \end{cases} \tag{14}$$

Considering the different dimensions, the effectiveness function of the agent is obtained after normalization:

$$R(k) = \lambda_1 \frac{E_{\text{agent}}(k)}{C_0(k)} + \lambda_2 \frac{V_{\text{Load}}(k)}{V_0(k)} \tag{15}$$

where, $C_0(k)$ and $V_0(k)$ represent the power purchase cost of users and load curve variance of controllable load without considering the blockchain environment; λ_1 and λ_2 represent the weight of economic decision model and stable operation model respectively.

IV. DESIGN FOR THE UNDERLYING TECHNOLOGY OF BLOCKCHAIN

The underlying technology architecture of blockchain in this paper includes five layers: data layer, network layer, consensus layer, incentive layer and interaction layer. The data layer is based on the blockchain structure, including the electricity consumption of each user and the peak-cutting plan of agents during this period. The network layer defines network communication protocols such as networking mechanism, data transmission mechanism, and data verification mechanism. The incentive layer achieves economic balance through profit sharing and encourages all nodes to jointly maintain the stable operation of the blockchain network. The consensus layer specifies how blockchain nodes reach consensus. In particular, in the interaction layer, this paper adopts the notary mechanism, and the cross-chain parties elect the verification node as the third party of mutual trust to realize cross-chain information interaction. Based on the blockchain sharding technology, the data layer, consensus layer, incentive layer and interaction layer suitable for the scenario are designed, as shown in Figure 2.

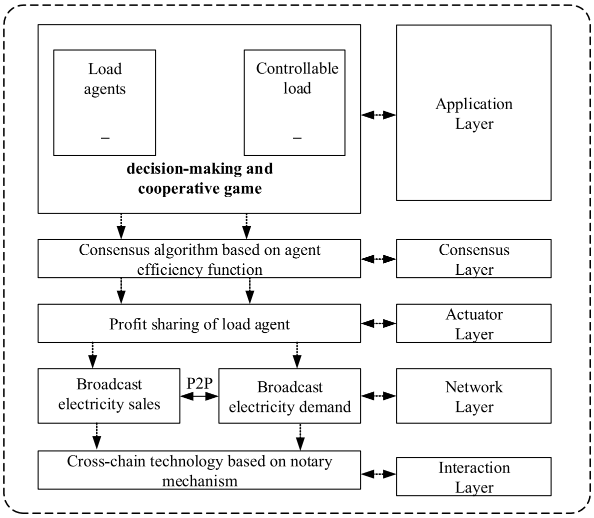


FIGURE 2. Mechanism at all levels of blockchain.

A. SECURITY CHECK MODEL BASED ON MULTI-CENTRALIZED ALLIANCE CHAIN

Based on the decentralized transaction chain, all the power transaction schemes must pass the network security check to meet the security constraints of the power system before the specific implementation. The coupled operation of the transaction chain and the power chain is designed, and a network security check method based on the multi-centralized power chain is proposed to realize the fair check and reasonable adjustment of the market agreement.

The multi-centralized alliance chain is selected by the power chain, with all node blocks storing the physical data of the P2P exchange in the power distribution system. Dispatching center agents (third-party non-profit organizations outside the power distribution system), large power generation companies (third-party profitable companies outside the power distribution system), and agents (profitable companies in the power distribution system) can all be used as power chain nodes. Without loss of generality and to simplify the model, the situation where multiple agents jointly maintain the power chain is considered in this paper. The power chain nodes are selected by voting by all agent nodes, and are comprehensively drafted to the reputation value of the agent nodes (the degree of participation in each scheduling). After the power chain node is determined, the verification authority node will perform the security verification of the specific transaction.

The power system security check is divided into two aspects: static and dynamic. The static security check with the upper and lower bounds of the line transmission power is mainly considered, and the dynamic security is reflected in the transmission power limit. The transaction verification set is composed of the market transaction power, power injection nodes and outflow nodes reached by all producers and consumers, which is:

$$\begin{aligned}\Phi M &= \Phi M_1 \cup \Phi M_2 \\ &= \left\{P^*_{i,j} \geq 0, \forall i, j, i \neq j\right\} \cup \left\{P^*_{grid,i}, \forall i\right\}\end{aligned} \tag{16}$$

where, ΦM_1 is the bilateral transaction set; ΦM_2 is the transaction set; $P^*_{i,j}$ and $P^*_{grid,i}$ are the transaction volume of agent i and agent j or the power grid after the market equilibrium point is reached through optimal decision.

The node injected power $P_i$of the consumer in the distribution system is:

$$P_i = \sum_{j=1,j\neq i}^{N} P^*_{i,j} + P^*_{grid,i} \tag{17}$$

where, N is the number of all user subgroups after clustering.

Based on the power network flow equation, the transmission power P_l on each line is calculated, and the upper and lower bound constraints are checked. If meet:

$$-P_{l,\max} \leq P_l \leq P_{l,\max} \tag{18}$$

Then all market transactions will pass the security check and be executed according to the original trading plan. If Equation (18) is not satisfied, then the adjustment decision is executed with the goal of minimizing the transaction adjustment amount. In the actual process of market transaction based on blockchain, the information of transaction block reached by producers and consumers on the transaction chain will form block adjustment information after the security check of the power chain checking node coupled with it.

Based on the above analysis, the controllable load power trading period is 15 min. The data structure of blockchain is shown in Figure 3:

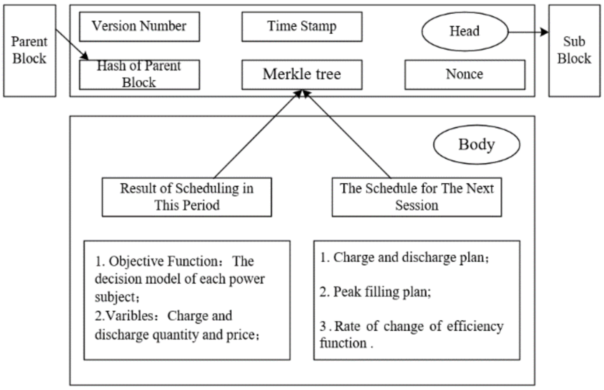


FIGURE 3. Data structure of blockchain.

B. DESIGN of INCENTIVE MECHANISM BASED OF PROFIT SHARING

The classic blockchain technology represented by Bitcoin and Ethereum adopts digital currency as the incentive mechanism. After each successful mining and confirmation, a new block is generated, and the winning accounting node of public selection gets digital currency. Rewarding bookkeepers with a piece of program in the form of digital currency implicitly conforms to the concept of assets in real society, which promotes the rapid development of blockchain technology. However, in the controllable load-load agent transaction scenario, if the accounting incentive mechanism of digital currency is considered, the price fluctuation of digital currency will also lead to difficulties in the settlement of power transactions. Therefore, the combination of bookkeeping incentives and the revenue of each agent are considered. As mentioned above, the load agents mainly act as the full node on the blockchain chain, responsible for maintaining the stability of the blockchain and keeping regular accounts. Therefore, part of the revenue of each agent can be considered as the incentive source, expressed as follows:

$$E_{\text{block}}(t) = \sum_{k=1}^{N} E_{\text{agent}}(k, t) \cdot \lambda \tag{19}$$

where, $\lambda$is the profit-sharing ratio of bookkeeping node given by each agent. If $E_{\text{agent}}(k, t) \leq 0$, $\lambda = 0$.

C. CONSENSUS ALGORITHM DESIGN BASED ON AGENT EFFICIENCY FUNCTION

In the controllable load-agent transaction scenario, power users operate on the chain as light nodes and do not have the ability to keep accounts. Therefore, this paper only needs to consider the billing right competition among load agent nodes according to the performance function described in Chapter 3. Each agent can obtain the higher probability of bookkeeping right according to the high efficiency function. Since the agent's efficiency function mainly reflects the operating income of the agent, the higher the income, the easier it is to obtain the blockchain bookkeeping right. Further, given the drawbacks of the current blockchain consensus algorithm, that is, the more equity in the node, the easier it is to obtain the bookkeeping right, which will easily lead to the control of the network power in the large load agents. Long-term operation will make the decentralized blockchain system evolve into a centralized network, which is not conducive to the long-term healthy development of the system.

In this optimal scheduling strategy, the classification of power users is mainly carried out by setting the SOC of EVs and the temperature of ACs. These characteristics directly determine the dispatching capacity of these two types of loads. This classification standard will lead to the agent with a smaller scheduling capacity to obtain less revenue. To sum up, the ledger revenue is used on the blockchain chain to dynamically balance the revenue among agents. Therefore, this paper proposes to take the rate of change of efficiency function as the consensus algorithm of blockchain. Whether a node can obtain the right of accounting mainly depends on its own sustainable and healthy development. The expression is shown as follows:

$$r(k) = \frac{R(k, t) - R(k, t-1)}{R(k, t-1)} \times 100\% \tag{20}$$

The main feature of the traditional Proof of Work (PoW) mechanism is that the node can get a result by doing some difficult work, but the prover can easily check whether the node has done the corresponding work by the result. The corresponding calculation process is shown as follows:

$$\begin{aligned} &\text{find } n \\ &s.t.\ SHA256(SHA256(h.n)) < TA \end{aligned} \tag{21}$$

where, $SHA256()$ is the 256bit hash encryption algorithm; h is the contents of the latest block; TA is the target difficulty value of the hash encryption; n is the random number.

The process of PoW mechanism is to find a n, and make it satisfy that the value after hash encryption is less than TA. Therefore, the smaller TA is, the more difficult mining is. Based on the above agent efficiency function, the consensus algorithm of this paper is shown as follows:

$$\begin{aligned} &\text{find } n \\ &s.t.\ SHA256(SHA256(h, n)) < r \times p \times TA \end{aligned} \tag{22}$$

where, p is the load duration for the agent to participate in the power grid; r is the rate of change of agent efficiency function.

The longer the load agent participates in the power grid and the higher the rate of efficiency function change, the lower the difficulty of hash calculation and the easier it is to obtain the blockchain bookkeeping right.

The consensus algorithm considering the rate of change of efficiency function ensures that the accounting right of each blockchain node is dynamically correlated with its income and contribution value to the grid, and promotes the decision-making behavior of each agent to operate in the direction beneficial to the grid. Combined with the above description of the decision model, incentive mechanism, smart contract solving algorithm and consensus algorithm of the blockchain node, the 24-hour operation process of the blockchain node in this paper is shown as Figure 4.

When a transaction is executed, the agent node with the largest $r(k)$ value completes the accounting, stamping the block to prove the validity of all transactions, and ensuring the post-facto traceability of all transactions. The block body mainly contains the scheduling results of this period, the charging and discharging plan required by users and the peaking and filling plan of agents in the next period. At the same time, the efficiency function of each agent is calculated to prepare for the next block consensus algorithm. The data mentioned are converted into binary merkle roots by the Hash algorithm and stored in the block header to ensure data privacy.

V. SIMULATION VERIFICATION

Matlab is used to solve the two types of smart contract decision models of controllable load/load agent, and the

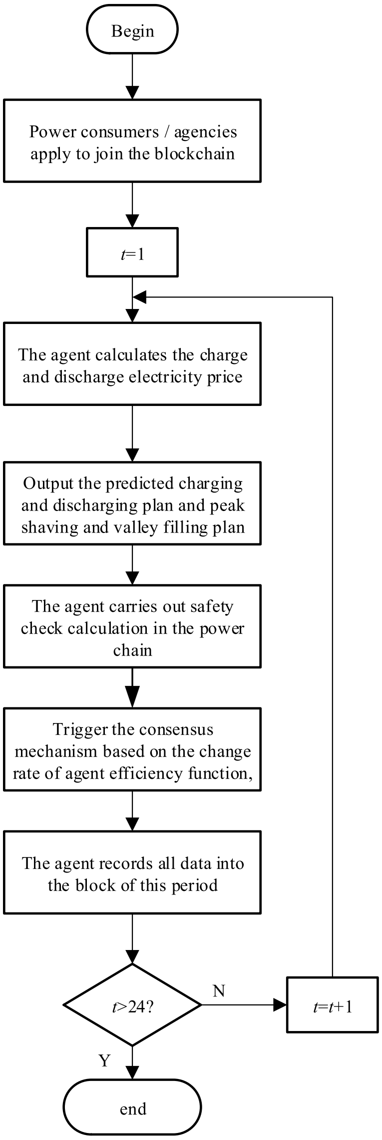


FIGURE 4. **Operation process of controllable load and load agents.**

feasibility of optimal scheduling of controllable load in the network was verified. Meanwhile, based on the Fabric simulation platform, single-chain and double-chain coupled blockchains have been employed for the simulation results, and the following assumptions are made:

A. ASSUMPTION

1) The simulation analysis is carried out for 500,000 residents in a typical summer day in a central city, in which the penetration rate of electric vehicles is 20% and that of air conditioning is 30%. Based on the statistical results of the 2017 NHTS, the start time and end time of users' daily travel are obtained [30].

2) It is assumed that all EVs participate in blockchain scheduling through agent V2G. For EVs, Roewe ERX5 is taken as an example.

3) It is assumed that in the ACs, T_{desired} is set at 27°C, and the maximum temperature for user participation in scheduling is evenly distributed between [27.5,29] °C and the minimum temperature is evenly distributed between [24], [26]. The values are set according to literature [33].

Other related parameters are set as follows:

1) The discharge income of agents is set at 0.5 yuan / (kW · h), the battery loss cost is set at 0.14 yuan/ (kW · h), and the entrusted agent fee of the user is set at 0.1 yuan/car/day. The values are set according to literature [32].
2) The profit-sharing ratio of the blockchain incentive mechanism is 0.1, and the agent efficiency function parameter is $\lambda_1 = \lambda_2 = 0.5$.

B. RESULT ANALYSIS

According to the results of the 2017 NHTS, the users' access and off-grid time showed normal distribution. The probability distribution of charging frequency and access time of EV users is shown in TABLE 1 when the user's electricity consumption is considered.

TABLE 1. **Initial charging time distribution corresponding to the charging frequency.**

Frequency of charging	I	II	III	IV
<=once	17.6,3.4	/	/	/
Twice	9.3,1.9	19.2,2.8	/	/
3 times	8.9,1.9	14.5,2.3	19.3,1.6	/
4 times	8.7,1.8	13.8,2.2	18.8,1.6	22.5,1.7

The k-means algorithm is used to carry out the first-stage clustering based on the user access and off-grid time. The final clustering center is divided into three categories, and the clustering results are shown in TABLE 2.

TABLE 2. **Cluster center of power users.**

Category	Departure time/h	Access time/h
I	8.32	14.21
II	14.96	19.01
III	6.24	18.65

EVs and ACs of each main class again detailed classification, EVs with the initial SOC from high to low as classification characteristics of ACs in order to classify temperature set point, finally get 9 subgroups. For different subgroups, based on their respective travel characteristics, SOC and temperature set point calculation model for its users. The charge and discharge conditions of the three user subgroups in cluster center I are shown as follows:

The EVs in user subgroup I has the largest surplus SOC, the maximum adjustable temperature range of the air conditioner, and the maximum amount of electricity that can

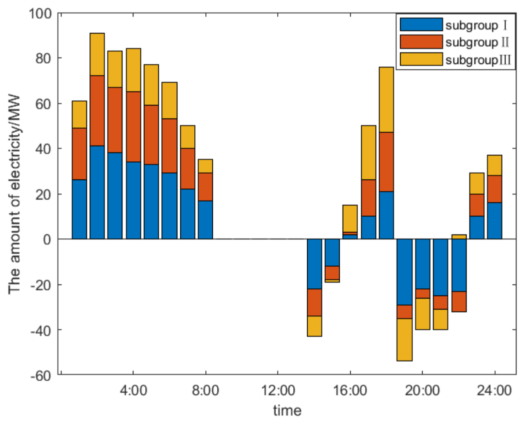


FIGURE 5. **Charge and discharge power of the three user subgroups in Center I.**

be dispatched. Therefore, the maximum discharge amount and charging time are mainly concentrated in the trough period, and the discharge to the grid is mainly in the peak period. The case of user subgroup 3 is just the opposite of subgroup 1. Its main purpose of entering the network is to meet its own demand for electricity, and the amount of electricity that can be dispatched is small. At the same time, the overall scheduling period basically conforms to the network entry and off-network period of the above clustering center. By integrating the charging and discharging conditions of nine power entities and adding them into the grid base load, the load curve is compared with the load curve considering the large-scale controllable load in the case of disordered electricity consumption, and the load curve is obtained as shown in figure 6.

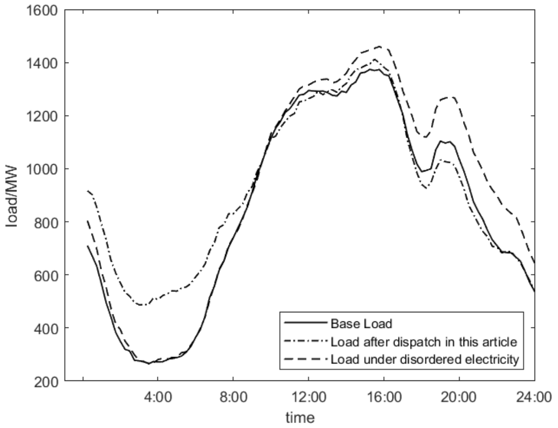


FIGURE 6. **Electricity load situation after considering the dispatching strategy of this article.**

As can be seen from the figure 6, if the controllable load calculated in this example is put into the network in a disordered state, that is, if the EVs enter the network and starts charging without considering discharge, and the ACs keep the most comfortable temperature at all times, "peak on peak" of the power grid load will result. In the valley period, the load curve basically coincides with the base load because the outdoor temperature drops and the EV charging is basically completed. In contrast, the optimization scheduling of power grid based on the blockchain can effectively control the setting temperature of the ACs within a reasonable range, transfer the charging of EVs from peak period to valley period, and achieve moderate discharge to the power grid during peak period, and finally realize the peak load shifting and valley filling of the power grid load.

The comparative analysis of economic benefits of different 24-hour scheduling policies is shown in TABLE 3.

TABLE 3. **Result analysis of agent income and user electricity cost.**

Scheduling policy	Electric car electricity costs / 10000yuan	Air conditioning load electricity cost / 10000yuan	Battery loss cost / 1000yuan	Consumer cost of electricity / 10000yuan	Income of load agent/ 10000yuan
Strategy of this paper	64.92	31.17	29.63	110.04	8.29
Disordered electricity	76.21	44.28	11.25	131.74	0

As can be seen from TABLE 3, in the case of disordered electricity consumption, the electricity purchase cost of electric vehicles and air conditioners is much higher than that under the dispatching condition, which is caused by the need to satisfy the electricity comfort of power users as much as possible. Because the discharge of EVs is considered under the scheduling in this paper, the damage to the battery of electric vehicles is great, so the cost of battery loss is far greater than the disorderly use of electricity. In this paper, power users rely on agents to adjust the charging and discharging period of electric vehicles, adjust the setting temperature of air conditioning, and obtain certain discharge compensation, and the total electricity cost is significantly reduced. However, the income of load agents mainly comes from the user's entrusted agent fee and the discharge income to the grid, which does not exist in the disordered state of electricity consumption.

C. PERFORMANCE COMPARISON

Based on the Ethereum platform, the double-chain and single-chain blockchain architecture is deployed respectively, and the performance simulation test was carried out. In the simulation, the block size is 1 MB, the byte size of each exchange is 1 KB, the byte size of the system physical data is 500 KB, and the block creation time is 1 h. The performance comparison results of double-chained and single-chained blockchains are shown in Table 4.

In the double-chain, where transaction data is deployed in chains with physical data, the transaction chain can process 15 transactions per second, while the single-chain can process 7 transactions per second. At the same time, the block

TABLE 4. Performance comparison between dual-chain and single-chain.

Blockchain	Pattern	Node numbers	Data	Byte/KB	Throughput	Consensus time/s
Single-chain	Public	9	Trading and electricity	1024	7	31.21
Trading chain in dual-chain	Public	9	Trading	1024	15	14.27
Electricity chain in dual-chain	Alliance	3	Electricity	1024	15	5.81

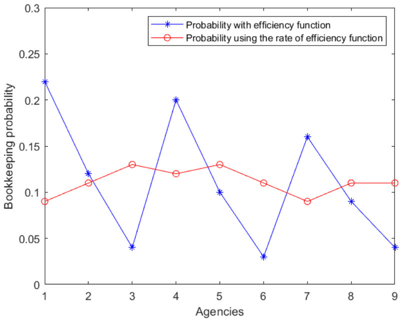


FIGURE 7. Comparison results of agent effectiveness function.

confirmation time includes the communication between nodes and the information verification time. Block confirmation on a single-chain includes the confirmation process of transactions and verification of adjustment information, with a total confirmation time of 31.21s. The confirmation of the transaction information in the double-chain blockchain is carried out in the transaction chain, and the confirmation time is 14.27s; the confirmation of check and adjustment information is carried out in the power chain. Due to the few nodes in the power chain, the confirmation time is short, which is 5.81s. The overall confirmation time of dual-chain is shorter than that of single chain blockchain. Therefore, in the P2P transaction scenario, dual-chain blockchain has higher transaction processing efficiency and performance.

In the trading chain, 9 load agents are considered as the full nodes of the blockchain, all of which have the right to compete for bookkeeping. From center 1 to center 3, the analysis is conducted in sequence. Compared with the simulation results in the literature [32], we take the period of 20:00 as an example and optain the efficiency function comparison results of agents, as shown in Figure 7:

As can be seen from Figure 7, the comparison of efficiency functions among agents is severely uneven. Agent 1, 4, and 7 have relatively large efficiency functions because their user subgroups have large scheduling capacity and make more profits. Therefore, the profit-sharing mechanism of agents considered in this paper is meaningful, and a part of the profits of all agents are accounted for in the reward block of the competitive incentive mechanism. In this paper, the change rate of efficiency function is selected as the blockchain consensus algorithm. Each agent first compares its scheduling effect in the previous period, and then competes with each other for the blockchain accounting right. The simulation results show that under the assumption of node rationality, the bookkeeping probability of each agent is between 10∼15%, and large agents will not monopolize the bookkeeping power,

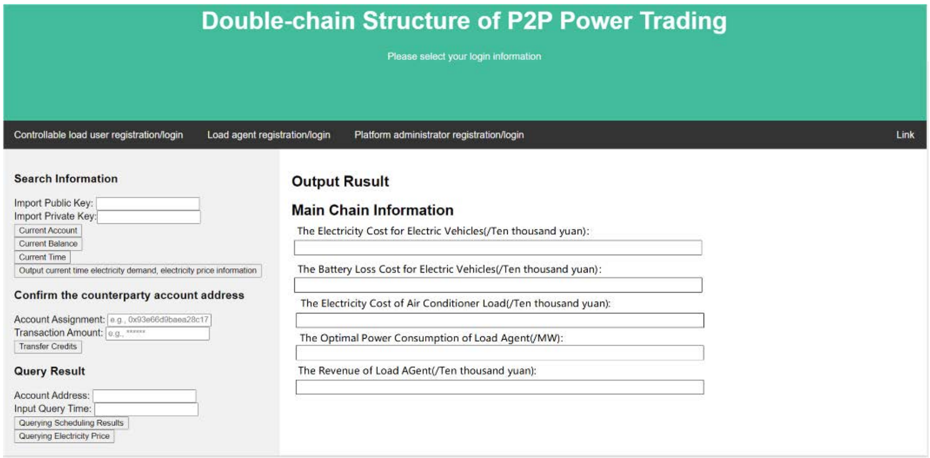
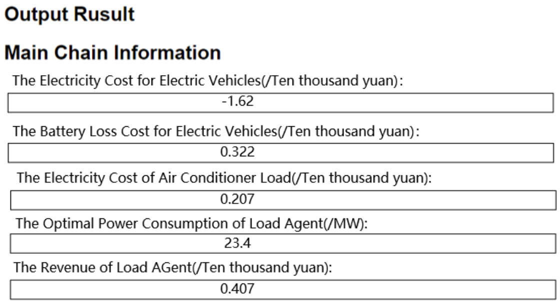


FIGURE 8. Smart contract test interface for blockchain.

effectively ensuring the long-term and reliable operation of the blockchain.

To test the feasibility of smart contract, Ethereum private chain is used to test the effect of smart contract of two kinds of decision model. The test interface of decentralized application of power transaction based on blockchain is shown in Figure 8 Input the transaction information of an agent and check it at 20:00 to obtain the electricity cost and power battery loss cost of EV users and the electricity cost and revenue of air conditioning load users under the agent, as shown in Figure 9 It can be seen from the figure that EV users under agent A at 20:00 mainly enjoy discharge benefits, but the power battery loss cost of EV at this time is high. In addition, under the background of time-of-use electricity price, the electricity cost of air conditioning load users is reduced. Compared with the above simulation results, the smart contract proposed in this chapter is accurate and effective.



Output Rusult

Main Chain Information

The Electricity Cost for Electric Vehicles(/Ten thousand yuan):

-1.62

The Battery Loss Cost for Electric Vehicles(/Ten thousand yuan):

0.322

The Electricity Cost of Air Conditioner Load(/Ten thousand yuan):

0.207

The Optimal Power Consumption of Load Agent(/MW):

23.4

The Revenue of Load AGent(/Ten thousand yuan):

0.407

FIGURE 9. **Output of smart contract at 20:00.**

VI. CONCLUSION

Based on the current situation of the booming development of distributed power trading, this paper proposes to use the double-chain blockchain to build a controllable load-agent trading platform to solve the problem of information asymmetry in power trading. The main innovations of this paper can be summarized as follows: 1) In terms of the smart contract, the power user/power agent decision model smart contract, which takes operation and maintenance cost and operation and maintenance efficiency into account, are established based on the basic principle of benefit optimization, and the power user's power resources of large-scale controllable power load are integrated, so as to achieve a win-win situation between the two types of power entities and complete the peak load shifting and valley filling of the power grid. 2) In terms of the underlying framework, on the basis of the original public chain of power transaction, the problem of security check after power users participate in the power grid is solved in the form of alliance chain, and the power transaction situation is checked and corrected. At the same time, according to the application scenario in this paper, the agent profit sharing incentive mechanism and the consensus algorithm of the change rate of agent efficiency function are proposed to realize the integration of the advantages of blockchain and power dispatching. In the future, the underlying technology of blockchain will continue to be optimized to make it more consistent with the actual situation of distributed power transaction mechanism.

NOMENCLATURE

A. CONSTANTS

T	the scheduling time of one period
B	the battery capacity of EVs
Δt	the duration of one scheduling period
η	the efficiency coefficient
A	the coefficient of heat conduction
δ	the range of indoor allowable temperature
λ_1	the weight of economic decision model
λ_2	the weight of stable operation model
N	the number of all user subgroups after clustering
n	the random number
p	the load duration for the agent to participate in the power grid
r	the rate of change of agent efficiency function
TA	the target difficulty value of the hash encryption

B. VARIABLES

$C_{\mathrm{ev}}(k)$	the demand cost model of EVs in the user subgroup k
$C_{\mathrm{ev}}^{\mathrm{buy}}(k)$	the cost of electricity purchase in the user subgroup k
$C_{\mathrm{ev}}^{\mathrm{loss}}(k)$	the battery loss cost in the user subgroup k
$C_{\mathrm{ev}}^{\mathrm{pro}}(k)$	the discharge benefits in the user subgroup k
N_k^{ev}	the number of users owning EVs in the user subgroup k
$P_{\mathrm{dch}}(i,t)$	the charge and discharge power of EVs
$x(i,t)$	the charging and discharging state of EVs in time period t
$W_{\mathrm{ch}}(t)$	the charging electricity price in time period t
$W_{\mathrm{loss}}(t)$	the unit loss cost of power battery in the time period t
$W_{\mathrm{pro}}(t)$	the discharge price in the time period t
$S_{\mathrm{rea}}^{\mathrm{SOC}}(i)$	the actual travel demand of EVs
$S_{\max}^{\mathrm{SOC}}$	the maximum power demands of user for travel
$S_{\min}^{\mathrm{SOC}}$	the minimum power demands of user for travel
$T_s(i)$	the home time of the aggregated user subgroup
$T_e(i)$	the leaving time of the aggregated user subgroup
$S^{\mathrm{SOC}}(i,t)$	the SOC of EVs at the end of time t
$C_{\mathrm{ac}}^{\mathrm{buy}}(k)$	the electricity cost of power users
$P_{\mathrm{ac}}(i,t)$	the power consumption of the ACs corresponding to the time period t
T_t^{out}	the outdoor temperature in the time period t
$P_{\mathrm{ac}}(i,t)$	the power of ACs

T_t^{in}	the indoor temperature (in °)
ε^T	the inertia of the system
T_{desired}	the most comfortable indoor temperature
$C_{\text{user}}(k)$	the economic cost function in the user subgroup k
$C_{\text{age}}(k)$	the agent commission in the user subgroup k
$W_{\text{age}}^{\text{ev}}$	the fee for EVs
$W_{\text{age}}^{\text{ac}}$	the fee for ACs
$E_{\text{sell}}^{\text{Agent}}$	the income from the sale of electricity
$W_{\text{dc}}(t)$	the discharge income of agent
$V_{\text{Load}}(k)$	the load variance in the user subgroup k
$P_{\text{BL}}(t)$	the electricity base load
P_{av}	the average power consumption load of power users during the whole period including EVs and ACs
$C_0(k)$	the power purchase cost of users without considering the blockchain environment
$V_0(k)$	the load curve variance of controllable load without considering the blockchain environment
ΦM_1	the bilateral transaction set
ΦM_2	the transaction set
$P_{i,j}^*$, $P_{grid,i}^*$	the transaction volume of agent i and agent j or the power grid after the market equilibrium point is reached through optimal decision
$SHA256()$	the 256bit hash encryption algorithm

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