Electric Vehicle Peer-to-Peer Energy Trading Model Based on SMES and Blockchain

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***Abstract*—As the energy internet develops, it will become possible to carry out peer-to-peer energy trading among prosumers. Different from traditional commodity trading, the process of P2P electricity trading will be affected by physical constraints such as network congestion. To avoid transaction failure, a superconducting energy storage unit is introduced. First, we established the overall structure of the electric vehicle P2P energy trading, and designed the blockchain network and smart contracts; then analyze the benefits of each user entity in the system, and optimize the user matching in the transaction process; After that, we used the co-operative game algorithm to realize P2P electricity transaction pricing model. Finally, the simulation and analysis results show that the use of superconducting energy storage has effectively improved the success rate and demand consumption rate of electric vehicle P2P energy trading.**

***Index Terms*—Superconducting magnetic energy storage, electrical vehicles, optimization, numerical simulation.**

I. Introduction

COMPARING with traditional vehicles, electric vehicles perform much better in energy saving, emission reduction, and reduction of human dependence on fossil fuels. However, the large-scale access of electric vehicles will affect the power quality, reliability, and economy of the power grid [1]. Adopting a Peer-to-Peer (P2P) power transaction mode can reduce the loss caused by the long-distance transmission of power, facilitate the absorption of the rich power of electric vehicles, and effectively reduce the impact of the charging load on the power grid.

As a brand-new solution, P2P energy trading can effectively solve the existing energy dilemma [2]. In [3], we proposed the use of superconductive magnetic energy storage (SMES) and blockchain technology to carry out P2P energy trading between electric vehicles and use the auction mechanism to maximize user benefits. Blockchain effectively connects distributed users, reduces the cost of trust between users, makes P2P energy trading possible. Based on existing research, we have studied the matching of users and the establishment of P2P transaction electricity prices based on cooperative games.

The rest of this paper is organized as follows. Section II introduces the core architecture of the system and focuses on the detailed introduction of the information layer where the blockchain is located. In section III, the revenue function of prosumers, the matching between users, and the setting of electricity prices based on cooperative games in the process of P2P energy trading are explained. Section IV describes the simulation experiment environment and test platform and analyzes the simulation results. Finally, we conclude the paper in Section V.

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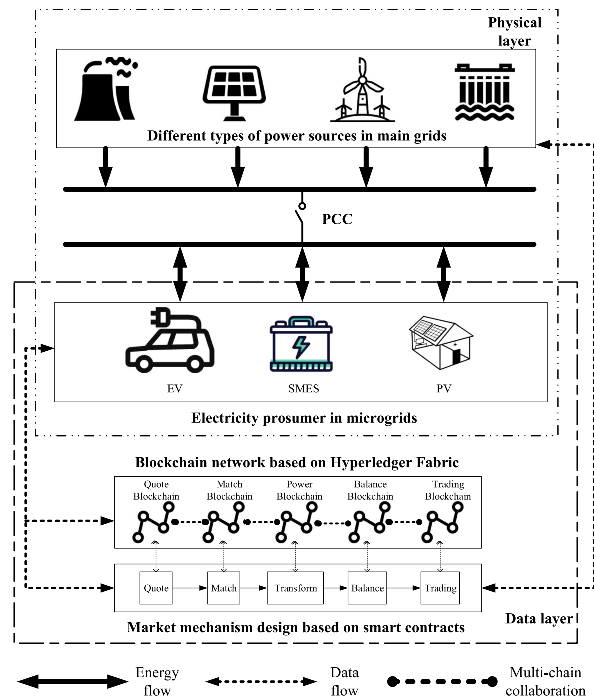

Fig. 1. Overall system architecture.

II. System Structure

A. Architecture

The architecture of the electric vehicle P2P energy trading system based on SMES and consortium blockchain is shown in Fig. 1. The system is mainly composed of a virtual layer and a physical layer. The subject of the transaction is an electric energy prosumer with a two-direction power flow, microgrid operators, and distribution network operators. The subject matter of the transaction is electricity and related ancillary services.

Mainly composed of distributed power sources, metering equipment, communication infrastructure, etc. The physical layer ensures that electricity can be safely and efficiently transmitted, data such as electricity, electricity bill, power flow which are collected and calculated in the physical layer can be passed to the data layer for further analysis and processing. It should be noted that physical devices require related network capabilities to perform related system upgrades and connect to the blockchain network.

The virtual layer is composed of information systems, market mechanisms, pricing mechanisms, and energy management systems. The information system relying on blockchain technology can effectively break down the information barriers between prosumers, so that market electricity prices, electricity supply and demand, policies and other information can be safely and efficiently shared among prosumers. In addition, featuring the characteristics of forced and automatic execution, the smart contract technology implements market mechanisms and pricing mechanisms and ensures the fairness of the P2P energy trading market.

B. Blockchain Network Design

The blockchain network is the core of the design of the EV P2P energy trading system. Hyperledger Fabric has the characteristics of modular development, maintainability, and scalability, we choose it to develop the blockchain network. Besides, compared to Ethereum, the Hyperledger Fabric blockchain network is more suitable for regional energy transactions [4].

Based on Hyperledger Fabric 1.4.3, a blockchain network is built, which is composed of three organizations: microgrid operators, distribution network operators, and regulatory agencies. Each organization includes related components to realize a consortium blockchain network with 3 channels. The channel technology is used to build a blockchain storage structure with transaction blockchain as the main chain and matching blockchain and electricity blockchain as the side chain. The collaboration between multiple chains is mainly realized through the chaincode in the Fabric. Different blockchain ledgers can query each other for data, and the final result can be write into the corresponding blockchain ledgers.

C. Smart Contract

The chaincode in Fabric is also called smart contract. In the blockchain environment, the use of smart contracts can ensure the safe, efficient and mandatory execution of related business logic [5]. This feature helps build P2P energy trading market mechanisms and pricing mechanisms. We use smart contract to realize user quotation, user matching, safety check, electricity transfer, transaction settlement, analysis and statistics.

Specifically, we first collect the quotations of the prosumers in the system at an interval of 1 hour. Then a weighted bipartite graph of the quotations was generated based on user roles and charge or discharge requirements, the Kuhn-Munkres algorithm was used to match the graph. Third, the security check is performed after matching. Fourth, users who fail the security check will first interact with the SMES. Finally, the transfer of electricity and automatic transaction settlement and analysis of transaction data will be carried out under an ensured safe power system.

III. Mathematical Modeling

In this section, we mathematically model the maximum weight matching and transaction price-setting issues in the EV P2P energy trading system containing SMES. Based on the analysis of the income of each prosumer, we try to maximize the relative income of the prosumer by using Kuhn-Munkres algorithm. Then, in order to ensure the reasonable distribution of user benefits in the cooperative mode, the nucleolus method in the cooperative game is adopted to price the P2P transaction electricity.

A. Benefit Analysis

Here we mainly analyze the user's charging and discharging benefits, to calculate the weight of user matching, and to facilitate conversion to bipartite graph-based user matching.

SMES can participate in P2P energy trading process and obtain trading profits. In addition, SMES also helps to increase the consumption rate of renewable energy and can obtain environmental benefits. The benefits of SMES are shown in (1).

$$R_{sm} = C_{ep} P_{sm} \Delta t - k_{sm} \left| P_{sm} \right| \Delta t \tag{1}$$

Where: R_{sm} is the revenue of SMES; C_{ep} is the electricity price; P_{sm} is the charge and discharge power of SMES, $P_{sm} > 0$ represents discharge process, and $P_{sm} < 0$ represents charge process. k_{sm} is the operation and maintenance cost coefficient of SMES.

The benefits of charging electric vehicles are shown in (2).

$$R_{cv} = -(p_{v2v} Q_{ij} + p_{v2v} \lambda_i D_{ip}) \tag{2}$$

In the formula: p_{v2v} represents the electricity price of the electric vehicle V2V power transaction; Q_{ij} represents the power of the charging vehicle and the power supply vehicle transaction; λ_i represents the power consumption per kilometer of the charging vehicle; D_{ip} represents the charging point P distance.

For discharge electric vehicles, the benefits are shown in (3).

$$R_{dv} = p_{v2v} Q_{ij} - \frac{p_0 Q_{ij}}{\eta} - p_0 \lambda_j D_{jp} - B_j \tag{3}$$

Where: p_0 represents the charging price of the electric vehicle; η represents the efficiency of power transmission; λ_j represents the power consumption per kilometer of the electric vehicle; D_{jp} represents the distance traveled by the electric vehicle to the charging point P; B_j represents the battery depreciation cost.

The revenue function of rooftop photovoltaic is mainly divided into two parts, electricity sales revenue and operation and maintenance costs, as shown in (4).

$$R_{pv} = C_{ep} P_{pv} \Delta t - k_{pv} P_{pv} \Delta t \tag{4}$$

In the formula: R_{pv} is the photovoltaic revenue; C_{ep} represents the electricity price; P_{pv} is the photovoltaic output power; k_{pv} represents the maintenance cost coefficient of the photovoltaic.

B. User Match

The improved Kuhn-Munkres algorithm based on bipartite graphs is used to match prosumers. Its objective function is as in formula (5), which means that microgrid operators can maximize the relative benefits of users through reasonable resource allocation.

$$\max \left\{ \sigma = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} Q\left[i, j\right] \times T\left[i, j\right] \right\} \tag{5}$$

In the formula, Q is the weight matrix of $m \times n$ dimension, and the element in it $Q[i, j] > 0$ represents the sum of the relative income R_i of electricity users $i (0 \leq i < m)$ and the relative income R_j of electricity users $j (0 \leq j < n)$, namely $Q[i, j] = R_i + R_j$. The distribution matrix T is a $m \times n$ dimensional matrix, $T[i, j] \in \{0, 1\} (0 \leq i < m, 0 \leq j < n)$, which indicates whether there is a P2P power transaction between the power purchaser i and the power seller j, $T[i, j] = 1$ indicates that the two carry out a P2P power transaction, and 0 indicates that the transaction has not been concluded.

The constraints are shown in (6), (7), and (8).

$$T\left[i, j\right] \in \left\{0, 1\right\} \left(0 \leq i < m, 0 \leq j < n\right) \tag{6}$$

$$\sum_{i=0}^{m-1} T\left[i, j\right] = L\left[j\right] \left(0 \leq j < n\right) \tag{7}$$

$$\sum_{j=0}^{n-1} T\left[i, j\right] \leq L^a\left[i\right] \left(0 \leq i < m\right) \tag{8}$$

Here, the improved KM algorithm designed in [6] is used to achieve the maximum weighted total matching among users.

C. Trading Electricity Price Setting Based on Cooperative Game

Blockchain technology effectively reduces the cost of trust between prosumers, ensures the credibility of shared data, and provides a reliable environment for cooperation among them. The key to cooperation among prosumers is to generate relative income and to achieve a reasonable distribution of relative income through the reasonable price of the energy trading [7]. For cooperative games, there are many methods. Comparing with other methods, the nucleolus method has good characteristics that have only one feasible solution. Therefore, the nucleus method is used to price P2P energy trading to improve user satisfaction.

In 1969, Schmeidler first use the nucleolar method to solve cooperative game problems. The cooperative game problem can be expressed as (N, v), where N is the set of participants, namely $N = \mathbb{C} \cup \mathbb{Z}$, v is the characteristic function, that is the prosumers benefits in this paper. The nucleolus is defined as for formula (9), $\widetilde{N} \neq \emptyset$ is the solution of the cooperative game.

$$\widetilde{N} = \left\{ x \in E(v) | \forall y \in E(v), y \neq x, \theta(x) < \theta(y) \right\} \tag{9}$$

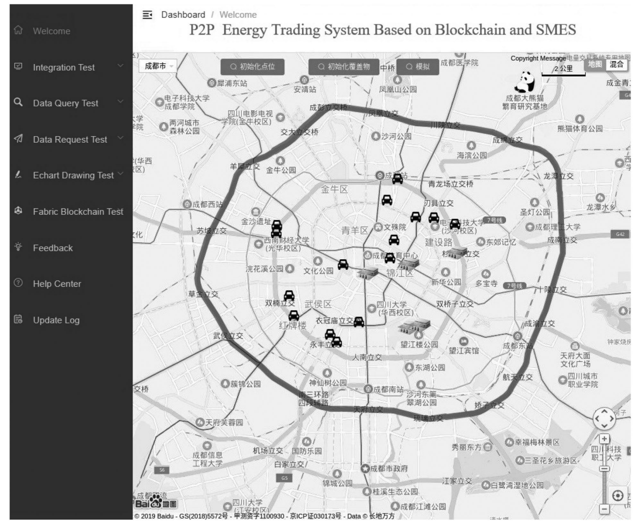

Fig. 2. Simulation system.

The dissatisfaction index $e(S, x)$ of the alliance S can be calculated by the formula (10).

$$e(S, x) = \pi(S) - \sum_{i \in S} x_i \tag{10}$$

In the formula, S is the alliance formed by users who buy/sell electricity; x is the user's relative income distribution plan, which represents the profit distribution set of producers and sellers; $\pi(S)$ is the cooperative profit of the alliance . The smaller the value $e(S, x)$, the more benefit the user can get from the cooperative game, that is, the more satisfied the user is with the result of this profit distribution.

The kernel is the solution when the user is most satisfied with the profit distribution, which achieves the Pareto optimum. For the solution of the nucleolus, it can be transformed into the linear programming problem of (11).

$$\begin{aligned} &\min \varepsilon \\ &s.t. \begin{cases} v(S) = \sum\limits_{i \in S_1} x'_i \\ v(S) - \sum\limits_{i \in S_2} x'_i \leq \varepsilon \end{cases} \end{aligned} \tag{11}$$

In the formula, ε is dissatisfaction; S_1 is an alliance formed by producers and sellers; x'_i is the profit allocated to the i-th prosumer, S_2 which is a collection of different cooperation methods. Solve this equation with scikit-learn package to get the optimal allocation.

Compared with the non-cooperative method, producers can obtain excess profits in a cooperative way, and the nucleolus method ensures the reasonable distribution of profits. From the producer's aspect, they are more willing to participate in a cooperative manner, thus ensuring the stability of the cooperative game.

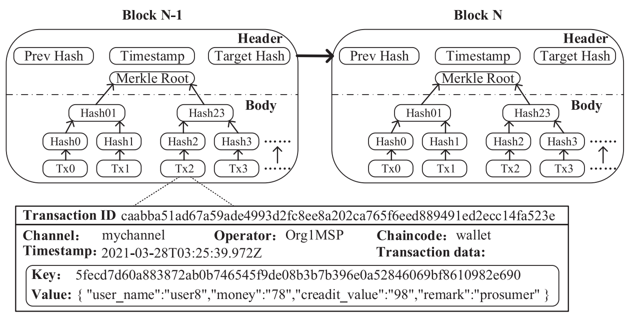

Fig. 3. Data in transaction blockchain.

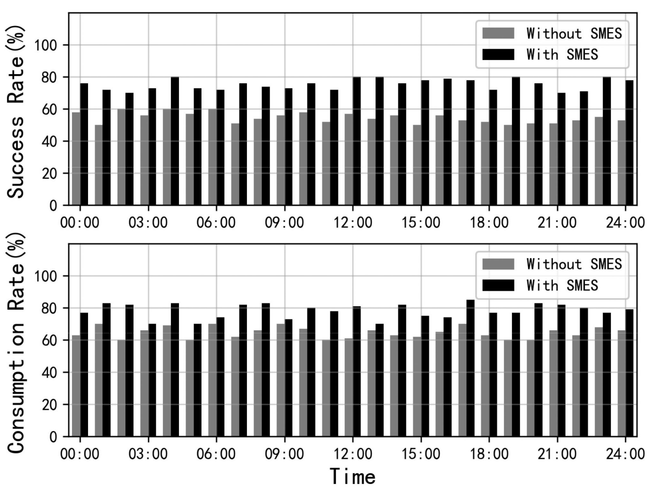

Fig. 4. The influence of SMES on success rate and consumption rate.

IV. Simulation Results

A. Simulation Environment

Four desktop computers configured with Intel i7-9700 CPU, 32G memory, 1TB solid-state drive, and CentOS 7.3 operating system were selected as the experimental carrier. The simulation interface is shown in Fig. 2.

Based on the map of some areas in Chengdu, the electric vehicle P2P energy trading system is constructed. The travel rules, electricity consumption rules, and P2P quotations of 15 electric vehicle users, 5 rooftop photovoltaic users, 1 SMES were simulated.

B. Simulation Result Analysis

The system is mainly driven by electricity prices, simulating the transaction process of producers and sellers, and analyzing the impact of SMES on P2P electricity transactions. Critical data is stored using blockchain to meet decentralized application scenarios.

Fig. 3 uses the transaction blockchain as an example to show the data stored in it. Unlike the traditional database storage method, asymmetric encryption, and JSON data format are more adopted in the blockchain.

Fig. 4 shows the average transaction success rates before and after adopting SMES technology were 54.5% and 74.5%, respectively. This means that superconducting energy storage can effectively reduce the transaction failure rate when the grid is congested. The renewable energy consumption rate before and after adopting SMES technology was 64.6% and 78.3%. The use of SMES will be more conducive to the reasonable consumption of electricity demand in the microgrid.

V. Conclusion

In this paper, we combine SMES technology and blockchain technology for electric vehicle P2P energy trading. Simulation and analysis show that blockchain technology can simplify the design of the underlying architecture of the P2P energy trading system, and the use of SMES technology can improve the success rate of user matching and improve demand consumption rate.

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