energies

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Blockchain-Enabled Charging Right Trading Among EV Charging Stations

Ruijiu Jin [1], Xiangfeng Zhang [1,*], Zhijie Wang [1], Wengang Sun [2], Xiaoxin Yang [3] and Zhong Shi [1]

1 College of Electrical Engineering, Shanghai Dianji University, Shanghai 201306, China; j_ruijiu1129@163.com (R.J); yxx_1031@163.com (Z.W.); 205141303nb@sina.com (Z.S.)
2 College of Urban Construction and Safety Engineering, Shanghai Institute of Technology, Shanghai 200235, China; 18616115850@163.com
3 College of Electronic, Guangxi University, Nanning 530004, China; 15895951726m1@sina.cn
* Correspondence: zhangxiangfeng@sdju.edu.cn; Tel.: +86-153-0086-1691

Received: 18 July 2019; Accepted: 7 October 2019; Published: 16 October 2019

Abstract: Increasing penetration of electric vehicles (EVs) gives rise to the challenges in the secure operation of power systems. The EV charging loads should be distributed among charging stations in a fair and incentive-compatible manner while ensuring that power transmission and transformation facilities are not overloaded. This paper first proposes a charging right (or charging power ration) trading mechanism and model based on blockchain. Considering all kinds of random factors of charging station loads, we use Monte Carlo modeling to determine the charging demand of charging stations in the future. Based on the charging demand of charging stations, a charging station needs to submit the charging demand for a future period. The blockchain first distributes initial charging right in a just manner and ensures the security of facilities. Given that the charging urgency and elasticity differences vary by charging stations, all charging stations then proceed with double auction and peer-to-peer (P2P) transaction of charging right. Bids and offers are cleared via double auctions if bids are higher than offers. The remaining bids and offers are cleared via the P2P market. Then, this paper designs the charging right allocation and trading platform and smart contract based on the Ethernet blockchain to ensure the safety of the distribution network (DN) and the transparency and efficiency of charging right trading. Simulation results based on the Ethereum private blockchain show the fairness and efficiency of the proposed mechanism and the effectiveness of the method and the mechanism.

Keywords: blockchain; electric vehicle; smart contract; P2P; charging right; Ethereum; charging stations

1. Introduction

The depletion of fossil fuels has made it necessary to develop alternative modes of transportation with EVs being the most preferred option [1]. With the support of the national new energy policy [2], EVs are inevitable in quantity growth [3]. The major obstacle is the deteriorating impact on the utility distribution system brought about by improper setup of these charging stations [4]. The charging of EVs will bring new challenges to the safety and stability of the power system [1]. In particular, it will lead to large-scale growth of grid load and further increase the peak-to-valley difference of DN load [5], resulting in transformer overload [1]. It is important to design a charging coordination mechanism for EVs, which maximizes the benefits of charging stations, avoiding overload of transmission and distribution equipment.

There is much research on the orderly charging control (OCC) of EVs. All EVs are regarded as independent energy consumers, and their charging is controlled by the unified EV control center [6].

This paper has been retracted.
A retraction notice was published on 29 October 2020 in *Energies* **2020**, *13*, 5660; doi:10.3390/en13215660

A multi-objective function is set to utilize the vehicle-to-grid (V2G) technology to minimize line loading, voltage deviation, and circuit power loss [7]. By analyzing the relationship among feeder loss, load rate and variance of load fluctuation in DN, an OCC method to reduce network loss is proposed [8]. The above research mainly focuses on the centralized control coordination of individual EV. However, with the rapid development of EVs, the drawbacks of centralized control platforms in credit systems, information security, revenue distribution and data sharing are beginning to emerge [9]. The randomness and decentralization of charging load become serious. The centralized control mode creates four problems:

1. The access of a large number of EVs leads to high operation cost of the control center and difficulty in meeting the requirements of safe operation of DN;
2. There are trust issues between the control center and EVs, which makes it difficult to ensure fairness, transparency and information symmetry of OCC;
3. The direct control of EVs ignores the individual will of the user. Especially in China's passive distribution network, it may cause the user to be dissatisfied;
4. Central institutions tend to cause information insecurity, which endangers the security of transactions and the privacy security of participants [9].

The OCC can reduce the peak-valley difference and improve voltage quality [10]. However, since the EV charging load fluctuates greatly and is related to the temperature and weather factors of the day, this makes the OCC difficult [11]. Therefore, it is necessary to study the load prediction method of the charging station, which provides support for OCC. The research mainly studies the load characteristics of EV charging stations from both time and space. In terms of time, according to the operating mechanism and charging power characteristics of the bus, a mathematical model of the capacity requirement of the electric bus charging station is established [12]. From the spatial point of view, this method selects similar days and performs short-term load forecasting on bus charging stations [13]. Therefore, it is important and meaningful for establishing the actual load model of the charging station.

In this study, the charging station with a large number of charging piles is taken as a unit, and the model of charging station load is established by the Monte Carlo method. On this basis, the concept of charging right is introduced. Charging right is a kind of digital asset. It represents the charging power quota of a charging station in a certain period. This research proposes a mechanism and model for optimizing the allocation of charging right among charging stations. Specifically, this paper divides the optimal allocation into two stages: initial planning allocation and market transaction.

In the first stage, according to the capacity margin of the transformer and the charging demand submitted by each charging station, the charging right is initially allocated to ensure that the total charging power does not exceed the limit. In the second stage, the charging right is traded among charging stations. According to the strong degree of charging intention and the flexibility of the charging load, each charging station decides the quotation, thereby realizing the market-oriented distribution of the charging right. The differences in charging intentions should be taken into account. To the efficiency of charging right trading, this paper introduces two trading mechanisms, double auction and P2P, into charging right trading market. When the buyer's price is higher than the seller's, the buyer and seller match the transaction in the double auction market; when the buyer's price is lower than the seller's, the buyer and sellers are listed on the P2P trading market.

Traditional trading market and rules are difficult to realize the safe and credible transaction of charging right. There are trust issues among charging stations because of the competitive relationship of charging right, and decentralized management and operation mechanism are necessary [14]. Solutions are proposed for the privacy problem [15–17]. A social-based privacy- preserving packet forwarding protocol, called SPRING, is proposed [15]. A new authentication protocol for VANETs in a decentralized group model by using a new group signature scheme is proposed [16]. An anonymous authentication scheme to avoid malicious EVs entering into the VANET is proposed [17].

Blockchain technology can solve the above problems by decentralization and de-trust. It is the ideal choice for implementing safety and transparency of transaction [18]. At present, the research of blockchain in the field of power energy is still in its infancy [19]. It is feasible to combine the operation of intelligent distributed energy systems on the blockchain [20]. The trading mechanism of distributed energy based on multiple signatures and blockchain is credible [19]. The sharing economy model of charging piles based on blockchain is the development trend of charging stations [21,22]. However, the above research is not yet combined blockchains with charging right trading.

For the OCC of EVs, this paper focuses on the allocation and trading of charging right. The second-generation blockchain technology, Ethereum and smart contract technology, is introduced into charging righttrading. In order to avoid the overload of power transmission and transformation equipment, a multilateral transaction of charging right technology is constructed, which realizes the distribution, de-trust transaction of charging stations, and maximizes the benefit. Based on the probability modeling of various random factors, the load model of charging station is obtained by the Monte Carlo method. We design a smart contract to execute the multilateral transaction of charging right on the private blockchain of Ethereum. Blockchain technology can realize the semi-decentralized power trading of EVs and charging stations, ensuring that power transactions do not have a single point of failure, and can also protect user privacy and achieve reliable payment of charging costs. EV charging price is more stable than before, and smart contracts reduce the price of disorderly charging to get the best return. Communication overhead can save at least 63.45%. The simulation results verify the validity of the mechanism and the blockchain trading platform.

2. Probability Model of Random Factor for Charging Station Load Modeling

EV is the main component of electric load [23]. The characteristic analysis of load is the basis of DN construction and capacity allocation of the charging station. It is important to support charging facilities planning of charging station [24]. In order to consider the time-varying charging station load, the number of charging EVs at a particular time is the key to load modeling. Also, the model is mainly related to the number of EVs entering the station, the time when the EVs enter the station, the charging time and other factors.

2.1. Probability Model of Vehicle Inbound Quantity

The charging process of the EVs in the charging station is random. The charging equipment and the charging EVs constitute a random service system. For the system, inputs that meet the following three conditions are called the simplest flow.

(1) Stationarity: In a particular time [a, a + t], the probability of reaching K customers has nothing to do with the starting time of the interval a, but is only related to the interval time t and the number of arriving customers K. The probability is $U_k(t)$.
(2) Non-after effect: The number of customers is independent of time intervals without time overlap.
(3) Limitation: The probability of reaching a limited number of customers at any limited time interval is 1.

For the simplest flow, the probability $U_k(t)$ of arriving at k customers in a time interval of L obeys the Poisson distribution.

$$U_k(t) = e^{-\lambda t}\frac{(\lambda t)^k}{k!}, k = 1,2,3\cdots \tag{1}$$

In the formula, L is greater than *0* and L is a constant. The charging behavior meets the three conditions. Therefore, the behavior of the EVs arriving at the charging station can be described by a Poisson distribution.

$$\mathrm{P}\{N = k\} = e^{-\lambda t}\frac{(\lambda t)^k}{k!}, k = 1,2,3\cdots \tag{2}$$

N is the number of EVs arriving at the charging station within the time interval $[t, t+\Delta t]$, then $n \sim P(\lambda)$. $P\{N=k\}$ is the probability of K EVs arriving at the station; t is the time interval.

2.2. Probability Model of Vehicle Arriving Time

The time of the first EV is $\tau_i(i=1,2\cdots)$, $\tau_0=0$, and $\xi_i=\tau_i-\tau_{i-1}, i=1,2\cdots$, the time interval of the second EV is a random variable of mutual independence and has the same distribution if $\xi_i(i=1,2\cdots)$. The arrival time intervals of successive vehicles follow an exponential distribution; the arrival time intervals of successive vehicles follow an exponential distribution.

$$\mathrm{T(t)}=\begin{cases}1-e^{-\lambda t}, & t\geq 0\\ 0, & t<0\end{cases} \tag{3}$$

In the formula, λ is an exponential distribution parameter of the vehicle arrival interval, and the number of vehicles at the same time obeys the Poisson distribution parameter. After knowing the distribution of arrival time intervals of successive vehicles, the arrival time can be calculated by Formula (4).

$$\begin{cases}\tau_i=\xi_i+\tau_{i-1}, i=1,2\cdots\\ \tau_0=0,\end{cases} \tag{4}$$

Due to peak-valley differences, a charging station in a central area of Shanghai was selected to determine the statistics of vehicle arrivals for 100 days. Probability model parameters for the number of arrivals and arrival time are shown in Table 1.

Table 1. Charger station average vehicle of each time.

Time	Means of Inbound Vehicles
23:00–06:59	38.53
07:00–08:59	43.78
09:00–11:59	24.19
12:00–13:59	54.93
14:00–16:59	31.74
17:00–18:59	66.04
19:00–20:59	34.31
21:00–22:59	73.26

2.3. Probability Model of Vehicle Charging Time

The charging time is determined by the state of charge (SOC) of the power battery [24]. SOC is related to many random factors such as vehicle load, driving distance, road condition and driving operation [25]. Because of the difference of the SOC, the charging time for the same charging facilities is different. If the inconsistency of charging facilities is considered, the charging time will be affected by more random factors [26]. It is described by probability and statistics [27]. The charging time approximately obeys the normal distribution of $\mathrm{N}(\mu_c, \sigma^2)$.

$$\mathrm{F}(T_c)=\frac{1}{\sigma\sqrt{2\pi}}exp\left[-\frac{(T_c-\mu_c)^2}{2\sigma^2}\right] \tag{5}$$

In the formula, T_c is the random variable of charging time, μ_c is the average of charging time, and μ_c is equal to 17.5, σ is the standard deviation of charging time, σ is equal to 6.57.

3. Charging Station Load Modeling Process Based on the Monte Carlo Method

The assumption of charging station load modeling is as follows:

1. The type of charger in the station is the same;

2. The influence of the type of EVs and the type of power battery on the charging power is not considered [28];
3. The EV charges when it comes to the station and the EV leaves the charging station when it reaches full charge.

The simulation step is 10 min, which is divided into eight periods. Taking the period 18:00–19:59 as an example, the calculation results are shown in Table 2.

Table 2. Discrete number of vehicle in charging stations.

t	18:10	18:20	18:30	18:40	18:50	19:00
n	5	4	5	9	7	4
t	19:10	19:20	19:30	19:40	19:50	20:00
n	7	3	8	11	8	4

$$S_2 = [(n_{2,1}, t_{2,3}), (n_{2,2}, t_{2,2}) \cdots (n_{2,12}, t_{2,12})] \tag{6}$$

$(t_{2,1}, t_{2,12})$ represents 12-time-points in Table 3 in increments of simulation steps. $(n_{2,1}, n_{2,12})$ is the number of charging EVs at the charging station corresponding to time-point $(t_{2,1}, t_{2,12})$.

$$l_2 = \left[(n^*_{2,1}, t^*_{2,1}), (n^*_{2,2}, t^*_{2,2}) \cdots (n^*_{2,12}, t^*_{2,12})\right] \tag{7}$$

Table 3. Transactions in the P2P period.

Limited Price Transaction	1. Buyer/Seller's designated transaction price and quantity of charging rights, 2. If there is a seller/buyer offer no less than that price, the transaction will be concluded, and the transaction price is the average value of the two parties' quotations.
Market Price Transaction	Buyer/Seller does not set a price but specifies a quantity to conclude the transaction at the best seller/buyer price in the current market
Cancel the order	Abandoning the right to sell/purchase charges and clearing the quotation information

$(t^*_{2,1}, t^*_{2,12})$ denotes the 12-time-points in Table 4 that increase with the simulation step size; $(n^*_{2,1}, n^*_{2,12})$ is the corresponding time point $(t^*_{2,1}, t^*_{2,12})$ the number of charging EVs at the charging station. Similarly, the number of charging vehicles at different permeabilities in other periods can be obtained.

Table 4. Parameter settings of electricity prices.

Time	**Charging Station Purchase Price from Power Grid/[yuan/kW·h]**	**Ethereum Electricity Price/[token/kW·h]**
Valley time (22:00–6:00)	0.32	32
Peak hours (8:00–11:00, 18:00–22:00)	1.12	112
Usual time (6:00–8:00, 11:00–18:00)	0.69	69

The Monte Carlo method is used to obtain the relationship between the number of charging EVs and the time. Combined with the single charger load model $P = P_n(U/U_N)^{-0.241}$, the charging station load model is described as follows. The daily load curve of the charging station is shown in Figure 1.

$$l = [l_1, l_2, l_3, l_4, l_5, l_6, l_7, l_8] \tag{8}$$

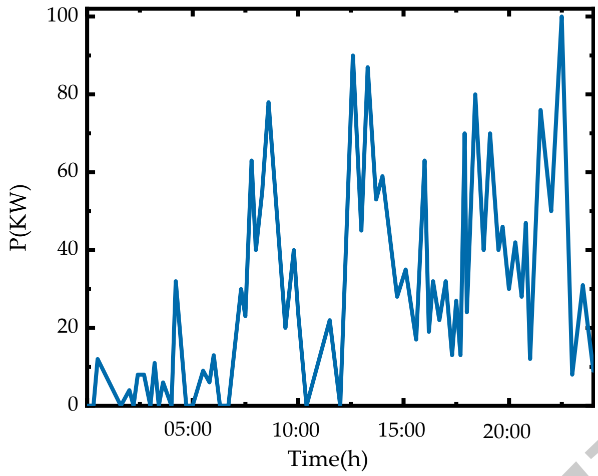

Figure 1. Active daily load curve of electric car charging stations at 39% penetration rate case.

Among them, $l_1 \sim l_8$ is the time interval matrix defined by Monte Carlo simulation results. Considering the time-varying load of the charging station, the load model of charging station is as follows.

$$\mathrm{P} = 1P_n(\frac{U}{U_n})^{-0.241} \tag{9}$$

The load model takes into account the time-varying load. It is of significance to study the impact of charging station load and its random fluctuation on the DN.

4. Charging Right Trading Mechanism and Model of Charging Station

To solve the problem of EVs' OCC caused by the surge in the number of EV, the decentralized autonomous charging control strategy of charging stations be studied [29]. The charging station as an intermediary for EVs and DN controls a small amount of EV and collects the EV charging demand [30]. According to the real-time operation status of DN, it can realize the efficient and economical charging control of sub-stations. Normally, transformers serving many charging stations are connected with both conventional and EV charging loads, which fluctuate greatly due to the uncertainty of arrival time and arrival status. Flexible mechanisms are designed to avoid the overload of transmission and transformation equipment [31].

In order to optimize the charging right distribution of the charging station, this paper designs the process of charging right allocation in the planning-market. In the market allocation, double auction and P2P charging right trading modes are introduced, as follows.

In the first stage, each charging station submits the charging power demand for the future period according to the EV status in the station. If the total charging demand does not cause transformer overload, all the requirements can be met. If the total charging demand power causes transformer overload, according to the proportion of the submitted power demand in the total charging power demand, the transformer capacity margin is allocated to each charging station. Although the method is fair, it does not take into account the urgency of the charging requirements, and it is impossible to allocate a limited charging right to the user who needs the most charging. Therefore, in the second stage, the charging right transaction among charging stations must be carried out. Charging stations with strong willingness and rigid demand can purchase charging rightto meet the demand. Some with weak willingness and elastic demand can sell a part of charging rightto gain revenue, thus realizing Pareto improvement.

Double auction and P2P trading market mechanism are introduced into the second stage of the charging right trading market. The charging station can independently quote the charging right [32]. When the buyer's quotation is higher than the seller's, the transaction price is the average value of the two parties' quotation. After the transaction in the double auction market, the remaining buyer's quotation is lower than the seller's quotation. These unknown quotations are listed in the P2P market. When the P2P market starts, the buyer's quotation is lower than the seller's quotation, so there is no transaction. In the market, participants need to modify their quotation or other quotation before they trade successfully. Of course, they can abandon the transaction and clear bidding information. The above mechanism ensures that the charging right are fairly and economically allocated to each charging station. Two mechanisms of charging right trading are shown in Figure 2.

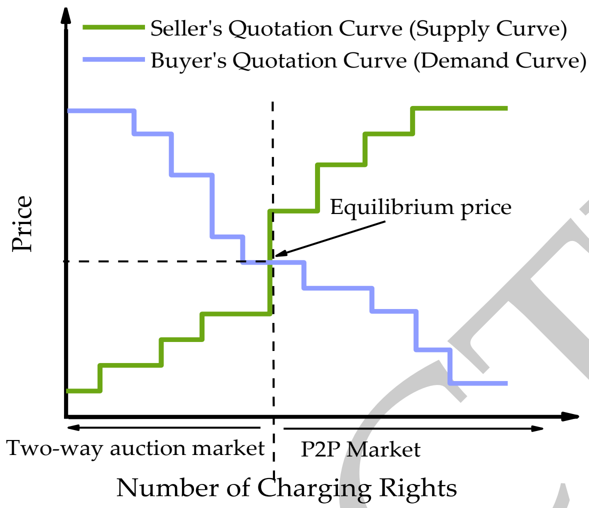

Figure 2. Two mechanisms of charging right trading.

The following two periods are taken as examples to show the trading process of charging right, as shown in Figure 3.

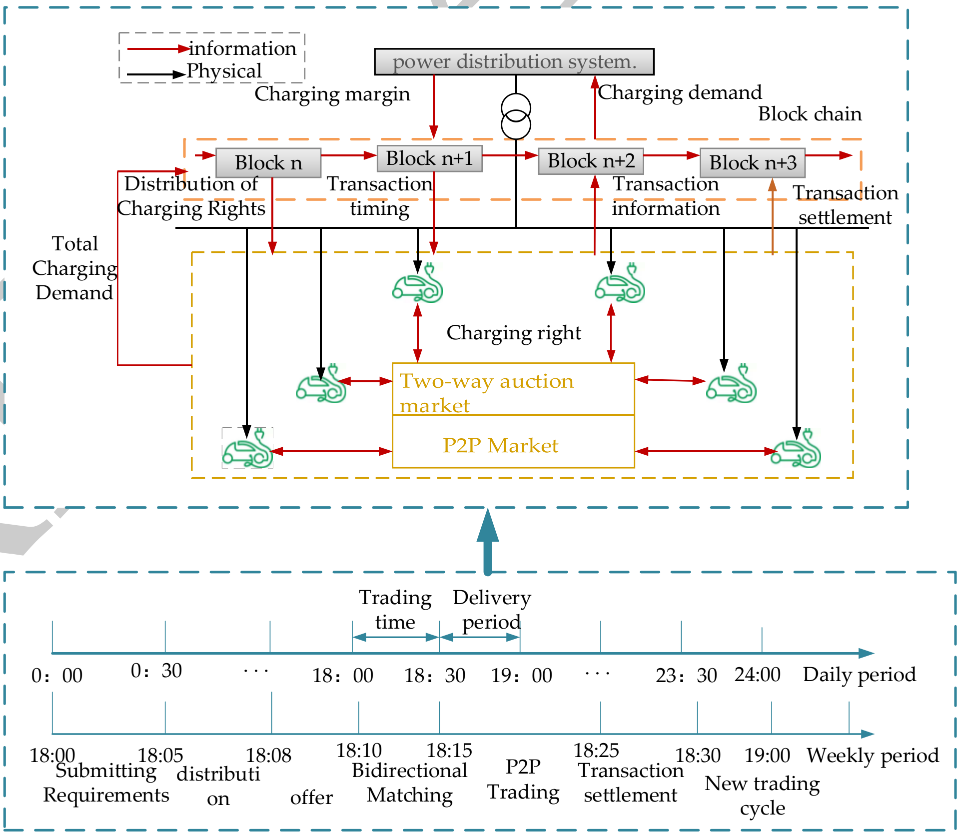

Figure 3. The overall architecture of charging right trading.

As a tradable digital asset, a charging right can carry out transactions for price and quantity in the double auction market and P2P market. At the same time, the blockchain completes information interaction and value transfer. Because it is impossible to obtain accurate charging demand for long-term charging stations [8], this paper divides a day into 48 periods, allocating and trading charging right in the next period.

(1) From 18:00–18: 05, all charging stations submit charging requirements at 18:30–19:00 to the blockchain according to actual needs.
(2) The grid company submits the request through the smart contract at 18:05. According to the historical data of the conventional load and the rated capacity of the equipment, the miners in the blockchain determine the total equipment load margin at 18:30–19:00 and record the total equipment load margin on the blockchain.
(3) The blockchain calculates the charge demand satisfaction ratio β_i within 18:05–18:07 according to the equipment load margin issued by the grid company and the total charge demand power. The calculation formula is as follows:

$$\beta_i = \begin{cases} 1, & P_M \geq \sum\limits_{j \in \Omega_E} P_j \\ P_{Ni} / \sum\limits_{j \in \Omega_E} P_{Nj}, & P_M \leq \sum\limits_{j \in \Omega_E} P_j \end{cases} \tag{10}$$

In the formula, P_M is the load margin of equipment in the next period issued by the grid company; Ω_E is the collection of charging stations; P_{Ni} is the rated power of the first charging station; P_j is the required power of the *j*-charging station.

In the blockchain, miners allocate charging rights and determine initial charging right according to the charging demand satisfaction rate [33]. When the total charging demand power does not exceed the load margin of power grid equipment, the charging demand satisfaction rate β_i is 1, and the charging power obtained by the charging station is the same as the declaration. When the total charging demand power is higher than the load margin, according to the ratio of the rated capacity to the total rated capacity, each charging station allocates the margin of the grid equipment and obtains the amount of charging right. The calculation formulas are as follows. $P^A_{i,E}$ represents the initial charging righs allocated by the *i*-charging station according to the charging demand satisfaction rate.

$$P^A_{i,E} = \begin{cases} \beta_i \times P_i, \ P_M \geq \sum\limits_{j \in \Omega_E} P_j \\ \beta_i \times P_M, P_M \geq \sum\limits_{j \in \Omega_E} P_j \end{cases} \tag{11}$$

The allocation method can suppress the impulse of the demand for charging [33,34]. When a charging station overstates the demand for charging, if the total demand is not exceeding the limit, the charging station will pay the assessment fee of deviated power because of the difference between the actual charging load and the declaration. If the total demand exceeds the limit, no matter how much the declared demand of charging stations is, the final rated power will be according to their respective rated power. Charging right are allocated in proportion to the total rated power. Charging stations with high rated power usually have to pay higher capacity charges to grid companies [33], so it is reasonable to obtain a larger share of charging right.

(4) When the total charging demand is greater than the equipment load margin, all charging stations are allocated charging rights according to the rules in (3). According to the elasticity of their charging loads, the quantity and price of charging rights that they wish to purchase/sell to other charging stations can be submitted from 18:07-18:10. The blockchain automatically allocates all charging right. Bidding information is arranged according to price: Seller's quotation is arranged

from low to high, buyer's quotation is arranged from high to low, and the same price is arranged according to the order of quotation time.

(5) After the bidding stage of the double auction, the blockchain clears the bidding queue at 18:10–18:15 according to the double auction rules: the highest price is the optimal bidding price, and the lowest price is the optimal selling price. When the optimal buying price is no less than the optimal selling price, the match is successful [34,35]. Then, the transaction price is the average arithmetic value of the bids offered by both sides, and the transaction volume is the smaller value of the declared transaction quantity [36]. After the transaction, the transaction volume is deducted from the bids of both sides and the bidding information be cleared. The above process continues to iterate until the bidding queue of one buyer and seller is all closed and cleared, or when the optimal selling price is greater than the optimal buying price. When the double matching is successful, all charging rights trading entities will settle transactions on the blockchain, and update the number of charging rights from 18:30–19:00 according to the trading results.

(6) If there are still unsuccessful matching bids after the double auction, the charging station can carry out P2P transactions from 18:15–18:25. The charging station can adopt the following three trading actions, as shown in Table 3.

If the buyer and the seller do not change the quotation in 18:05–18:07 and there is no new charging station quotation (no one adjusts the quotation). Meanwhile, if the buyer's quotation is lower than the seller's, there is no turnover in the P2P market. If there is a charging station to adjust the quotation (for example, a charging station updates its charging requirement from 18:30–19:00. A transaction may be concluded if the amount of charge required is reduced or the charging elasticity is increased, thereby reducing/increasing the selling/purchasing quotation of the charging right). If the buyer and seller abandon the P2P transaction and no longer buy/sell charging rights, they can withdraw the order and clear quotation information. When the matching of P2P transactions is successful, all charging rights trading entities can settle transactions and update the number of charging rights from 18:30–19:00.

(7) All charging stations should pay 18:30–19:00 charging charges to the grid company according to the final allocation and trading rights, and the charges should be settled on the blockchain.

(8) According to the final charging right from 18:30–19:00, the charging station should provide a charging service. It installs smart meters with runnable blockchain nodes to measure the power. Data interaction is generated through a built-in communication module and smart contract. The miner packs the data into the blockchain [33]. Smart meters complete the process independently without grid companies. To maintain security and stability of the DN, when the actual charging power is greater than the charge right, charging stations will be financial penalties.

The above-mentioned blockchain-based charging right trading mechanism is suitable for decentralized charging control. Considering the maximum load capacity of transformers and charging demand, the objective function is to maximize charging revenue of charging stations in each period.

$$\max \sum_{i \in \Omega_E} \left(U_i(P_{i,E}) - C_i(P_{i,E}) \right) \tag{12}$$

In the formula, Ω_E is the collection of charging stations; $P_{i,E}$ is the final charging right of the i-charging station in a certain period, $P_{i,E}$ is greater than 0; $U_i(\cdot)$ is the revenue function of the i charging station; $C_i(\cdot)$ is the cost function of the i-charging station.

The constraints of the clearing model are shown in Formula (13)–(15):

(1) Constriction on charging rights of the charging station. At each period, the final charging right is the sum of the initial charging right and the charging right purchased/sold through the double auction and P2P transaction:

$$P_{i,E} = P_{i,E}^{A} + \sum_{j \in \Omega_S^i} P_{i,j} \tag{13}$$

In the formula, Ω_S^i is a collection of charging stations that carry out charging right trading with the *i*- charging station; $P_{i,j}$ is the trading volume of charging right between the *i*-charging station and the *j*-charging station; $P_{i,j} > 0$ represents the buying right of charging for the *i*-charging station; $P_{i,j} < 0$ represents the selling right of charging for the *i*-charging station.

(2) Transformer capacity constraints. Assuming that the charging station, in the area of Ω_E , is under the transformer with the maximum load capacity of P_M , the sum of the total charge right and the conventional load of all charging stations in a period is not larger than the maximum load capacity of the transformer.

$$\sum_{i \in \Omega_E} P_{i,E} + L_{0,i} \leq P_M \tag{14}$$

$L_{0,i}$ represents the conventional loads in this period.

(3) Quantity constraints on charging rights transactions. The number of charging rights traded among charging stations should be less than the total charging rights owned by the seller at this time:

$$\begin{cases} 0 \leq \left|P_{i,j}\right| \leq P_{i,E} & P_{i,j} \leq 0 \\ 0 \leq \left|P_{i,j}\right| \leq P_{j,E} & P_{i,j} > 0 \end{cases} \tag{15}$$

This paper does not run the above optimization model on blockchains (because blockchains are not friendly to the solution of optimization problems) but runs the double auction algorithm and P2P algorithm on blockchains. The results of the double auction and P2P transaction reflect the objective function and constraint conditions of the above optimization model.

5. Multilateral Trading Method of Charging Rights Based on Ethereum Smart Contract

5.1. Blockchain Technology and Ethereum Smart Contract

According to the time sequence, blockchain is a data structure that combines data blocks in a chain. Based on the cryptography method, it guarantees that the decentralized shared general ledger cannot be falsified and unforgeable, and can safely store simple, sequential and verifiable data [37]. The blockchain solves the problems of high cost, low efficiency, and insecure data storage that are common in centralized organizations.

Ethereum is a new programmable development platform based on blockchain technology [38]. Developers can execute complex code through the built-in virtual machine, making it easy to publish and trade digital assets, build and run decentralized applications. In Ethernet, smart contracts are computer programs deployed on Ethereum that can automatically execute [39]. They can process information, receive, store and transfer digital assets. Each user can act as a "miner" to collect all the transaction and transmission information, and solve a mathematical problem based on the Ethash algorithm [40]. The "miner" who solves the fastest will obtain the final accounting right. They are responsible for packaging, disseminating all the data they record, and obtaining economic incentives [18]. Through this mechanism, Ethereum allows all miners to record and maintain system data together.

Ethereum can trade digital assets and realize value transfer, which provides a solution for building a multilateral trading platform for charging rights [36]. Through the platform, all charging stations and grid companies can access Ethereum private-chain and transfer and settle the charging rights digital assets. At the same time, the smart contract can realize trusted transaction without a third party, which provides security for the transfer of charging rights among charging stations.

At present, the computing power and response speed of blockchains are limited [38], and a large number of transactions can easily cause congestion. It is important to increase the speed of calculation and the immediate completion of transactions. Firstly, blockchain developers are exploring strategies such as increasing block sizes, developing technologies include sharding, sidechains and payment channels. Secondly, in the current period, the mechanism is to allocate and trade the charging rights in the next period, for example, pre-allocating 18:30–19:00 charging rights transactions and demand in 18:00–18:30. Thirdly, the transaction mechanism only involves a small number of nodes, which can be deployed in the Ethereum private-chain with adjustable mining difficulty instead of in the crowded public chain. The latter can effectively improve the transaction speed of the blockchain.

5.2. Multilateral Transaction Smart Contract for Charging Rights

The multilateral trading process of charging rights in a trading cycle is divided into four stages, including charging demand submission, charging rights double auction, charging rights P2P trading, delivery and settlement. The charging demand submission stage includes the standard-setting function, charging demand submission function and charging right allocation function; the double auction stage includes the biding function and matching function; P2P transaction stage includes the price limit transaction function, market price transaction function and withdrawal function; the delivery and settlement stage includes the payment function and margin refund function. The multilateral trading flow of charging rights is shown in Figure 4.

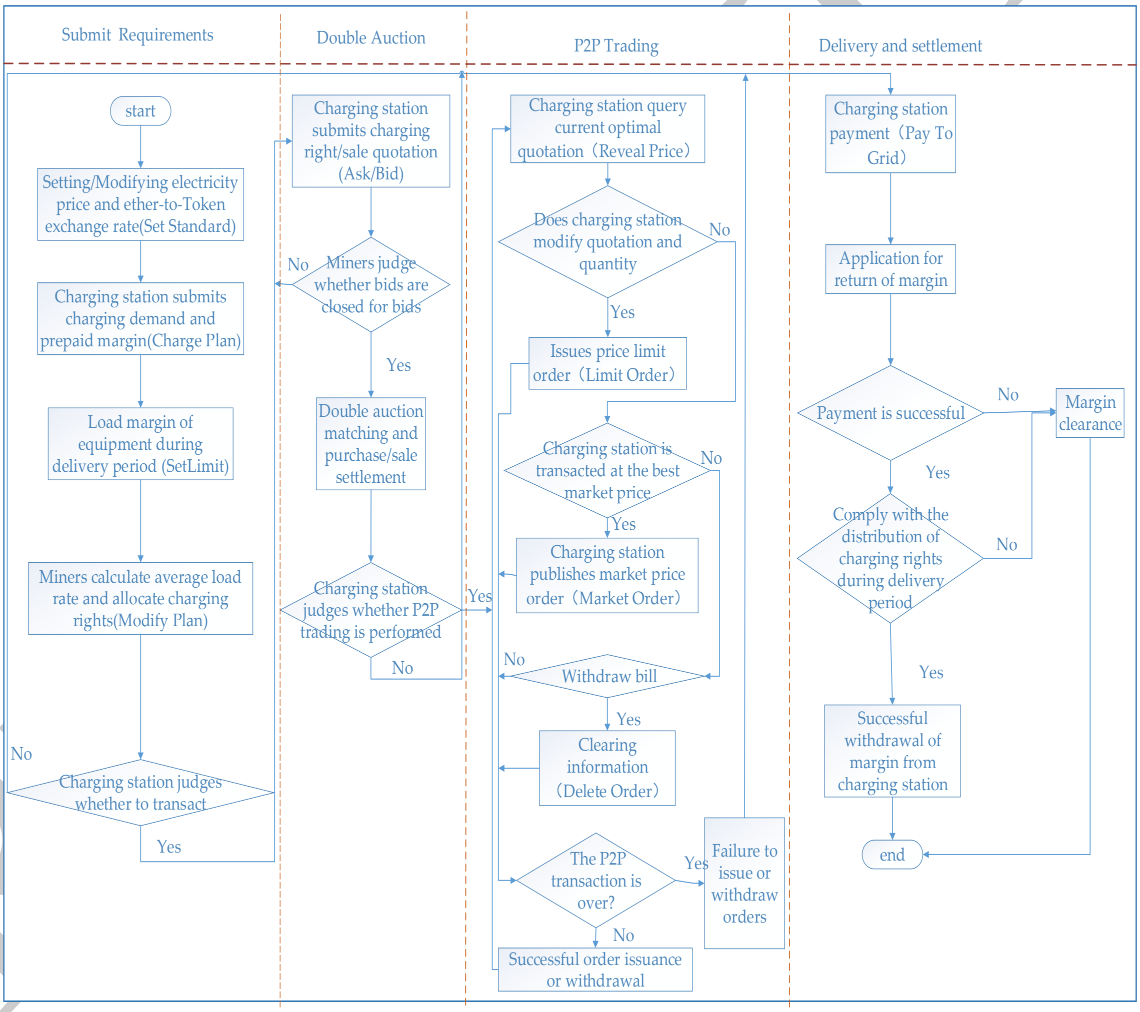

Figure 4. Flowchart of charging right trading on Ethereum.

1. Charging Demand Submission

- Set Standard

Members of the blockchain (including grid companies, charging stations) are invoked before the start of the new trading cycle. The function set/modify the market standard electricity price, the Ethereum and the trading platform to pay the currency Token exchange rate. On the one hand, market electricity price provides real-time electricity price information for charging demand submitted; on the other hand, and it provides a price reference for charging right transaction pricing. Therefore, the specific value is based on local time-of-use price. Because the price of Ether currency fluctuates greatly, this paper chooses ERC20 Token as the payment currency, and revises Ether currency according to the exchange rate of Ether currency and CNY (the exchange rate of Ether currency and CNY is about 1eth = 1349 yuan on 15 May 2019) at the beginning of each trading cycle by the grid company. With Token's exchange rate, the exchange rate can be modified to achieve 1 yuan = 100 token, which can stabilize the price fluctuation of Ether currency.

All members (including grid companies, charging stations and miners) of the blockchain can call functions to publish information such as standard price and exchange rate, and miners package information to create new blocks. In order to ensure correct electricity price and real-time exchange rate recorded on the blockchain, they independently verify information such as electricity price and exchange rate, add the block containing the correct information to local nodes, and refuse to add the block containing malicious information. In this way, the grid company or a charging station can avoid a malicious declaration of electricity price and real-time exchange rate, which reflects the idea of transparent blockchain and multi-check. Besides, the caller of the function in the Ethereum smart contract is the grid company or the user of the charging station, but the executor of the function is all "miners". That is to say, the caller pays an amount of gas (in the Ethereum, smart contract callers pay miners to perform function operations and package trades) to call the functions in the smart contract, and the "miners" receive the call request and merge. The miner who can solve the math problem fastest can publish the trading information to the blockchain and get a particular reward, to encourage all the miners to record and maintain the data of the charging right trading platform. The following functions are called and executed in the same way.

- Charge Plan

Before the completion of charging demand submission, the user of the charging station calls the function to submit the charging demand within the delivery period to the smart contract, and then the user should pay the deposit to the address of the smart contract. The miner confirms the charging demand information and the transfer result, then packages the charging demand power and deposit information into the blockchain if there is no mistake. The deposit formula is as follows:

$$D_i = \pi_t \times P_i \times \Delta t \times 2 \tag{16}$$

D_i is the margin calculated by the blockchain, π_t is the standard transaction price set by the grid company at the beginning of the trading period (which should be determined according to the time-sharing price), P_i is the charging demand submitted by the charging station during the delivery period, and Δt is the delivery period. In this study, the whole day is divided into 48 periods. The length should be 30 min.

The deposits submitted are mainly used for the following purposes:

1. Payment and settlement of charging rights in the double auction and P2P trading market.
2. At the end of the trading period, deposits is used to pay the charging cost of delivery time to the grid company.
3. During the delivery period, deposits can guarantee the charging power limit. If the charging power of the charging station is higher than the charging right obtained, the deposit will be deducted.

In the Ethereum, time control can be determined by Unix timestamp [41]. It is defined as the total number of seconds since 00:00:00 on 1 January 1970. Ethereum blocks need to contain current timestamp information, and miners determine the timeliness of user-initiated operations. Therefore, the timestamp is used to determine the timeliness of the user's operation in the smart contract, and the miner does not package the function of call information that does not belong to the current period into the block. The same is true for the following functions.

- Set Limit

After the submission of the charging demand, the grid company calls the function and issues the request for calculating the load margin of the device to the blockchain. According to the historical data of the conventional load recorded on the blockchain and the rated capacity of the equipment, the miners perform the logical operation of the smart contract function to determine the load margin of the equipment during the period of power delivery, then record the data. In this process, grid companies cannot modify conventional load, rated capacity of equipment and other data, nor can they modify the logic code in smart contracts. The blockchain mechanism ensures the credibility of the overall device load margin [42].

- Modify Plan

The grid company calls the function and pays a certain gas price to issue charging rights allocation requests to the Ethereum. According to the total charging demand and equipment load margin, miners perform smart contract calculation. They calculate the average load rate and allocate charging rights according to formula (10)–(11). Finally, they pack the blockchains and update the charging rights during the delivery period. If the total charge demand is no larger than the equipment load margin, then the charge demand satisfaction rate is 1. In other words, the charging right is the same as the declared demand and directly enters the delivery and settlement stage. If the total charge demand is large than the equipment load margin, then the charge demand satisfaction rate is less than 1; the charging right is less than the declaration. For the demand, charging stations can enter the double auction stage and trade independently.

2. Double auction stage

- Bidding Function of Charging Right Purchase/Sale (Bid/Ask)

Before the bidding stage of the double auction is over, the charging station calls the Bid/Ask function of the smart contract according to its needs and submits the charging right purchase/sale quotation to the blockchain. Miners judge the timeliness of bidding. If the bidding is not closed, the bidding information is added to the purchase/sale bidding queue, and the bidding queue is sorted according to the price from large to small/from small to large. Finally, they package all the information into the blockchain.

- Double auction matching function

After bidding for double auction, the grid company pays for calling this function, and the miners carry out double auction matching for the charging stations that have submitted the purchase/sale intention and update the charging rights during the delivery period. The flow chart of function arithmetic is shown in Figure 5.

Through the logic operations set by the smart contract, miners perform the following functions: match the purchase/sale offer queue with the double auction mechanism; settle the transfer to the charging station that was successfully matched (the settlement price is the average price quoted); updating the charging right of the delivery period for the charging station that successfully trades.Double matching stops until one of the buyers and sellers' quotation queues is cleared or the optimal offer price is greater than the optimal bid price.

```
Asks is ranked from small to large according to Ai, supplyi is the corresponding tender quantity, n is the total number of the seller queue, the price is Ai, and the seller's quotation queue is ranked as Asks.
Asks = {( A1, supply1),…,( An, supplyn)}
Buyer's Bids are ranked by price Bi from large to small. Demandi is the corresponding bidding quantity, m is the total number of the seller queue.
Bids = {( B1, demand1),…,( Bm, demandm)}
while Asks! = {} & Bids! = {} & B1 ≥ A1 do
    Transaction price: P = (A1+B1) / 2
    Number of transactions: M = min (supply1, demand1)
    Transaction transfer: P*M
    Renewal of Charging Right Allocation Quantity: Seller Reduces M, Buyer Increases M
    Update of Seller's Bidding Quantity:( A1, supply1) ← ( A1, supply1 – M )
    Buyer's tender quantity renewal:( B1, demand1) ← (B1, demand1 – M )
    if demand1 == 0 then
        for ( Bi, demandi) ∈ Bids do
        ( Bi, demandi) ← (Bi+1, demandi+1 )
        end for
    else
        for ( Ai, supplyi) ∈ Asks do
        ( Ai, supplyi) ← (Ai+1, supplyi+1 )
        end for
    end if
end while
```

Figure 5. Double auction matching algorithm.

3. P2P Trading Phase

After matching in the double auction stage, the highest price of the buyer is lower than the lowest price of the seller. If the charging station is strongly willing to buy and sell the charging right, the best quotation can be offered according to the current market (the seller's lowest quotation and the buyer's highest quotation). A charging station can choose to adjust the quotation and issue a price limit order to the blockchain or trade at the optimal market price [38]. If the willingness is not strong, charging station can abandon the transaction and withdraw the bill. Miners judge the timeliness of trading behavior, such as the P2P transaction not being closed. Then, the charge station matches the transaction or clears the quotation information. Finally, the trading results are packaged into blockchain records. The process is shown in Figure 6.

- Reveal Price

From the end of the matching to the end of the P2P transaction stage, the uncleared charging stations can call the function to query the optimal offer. Also, the buyer can inquire the current lowest sale price, the seller can inquire the current highest buy price to decide to adjust the price, issue limit price, issue market price to trade or withdraw the order to abandon the trade.

- Limit Order

If the buyer/seller decides to modify the quotation or quantity, the function can be called to modify the quotation and quantity and issue a price limit order to the blockchain. From the end of the matching to the end of the P2P transaction stage, the order can be responded to by other charging station users, and the quantity can be traded at a price set by the price limit order until the transaction amount reaches the price set. After the response, the miners will complete the transaction settlement, transfer through the smart contract, and modify the charging rights of both sides during the delivery period.

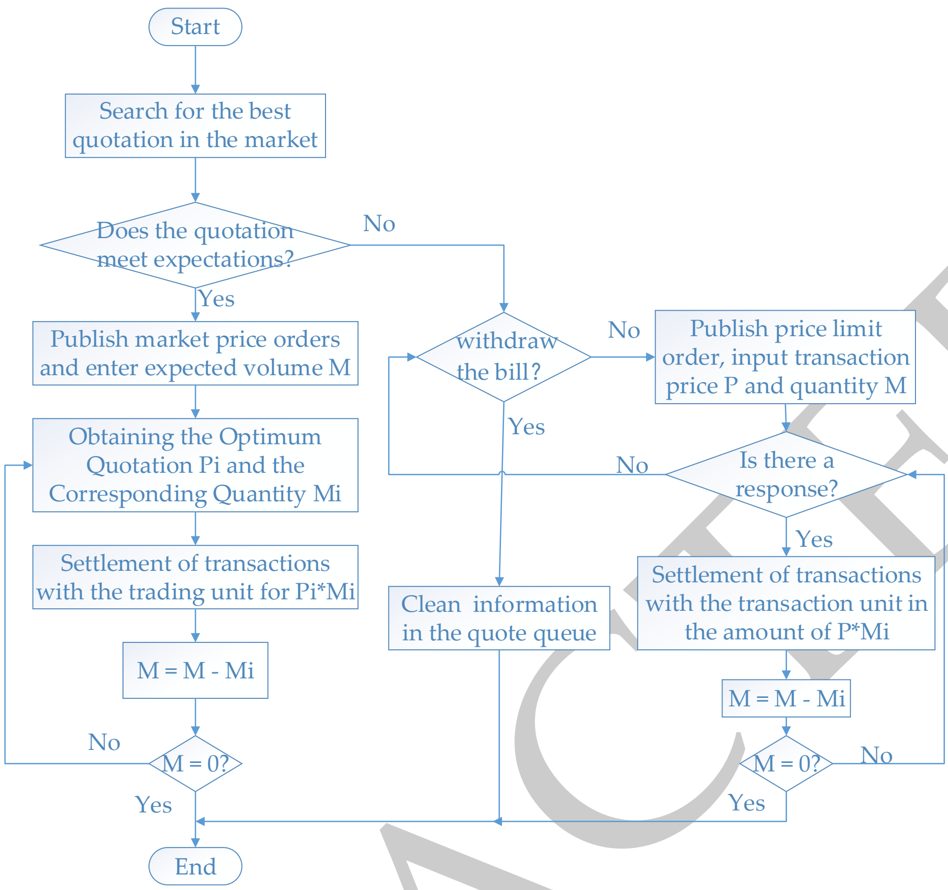

Figure 6. Flowchart of charging right trading in the P2P market.

- Market Order

If the buyer/seller decides to trade at the optimal price in the current market, the function is called to input the planned number of transactions. According to the optimal market price, the miner executes the logic of the smart contract function, matching the transactions until the matching is complete, the quotation queue is empty, or the transaction is terminated. At the same time, the miner complete the settlement and transfer, modify the charging rights of both parties and finally update all relevant information.

- Delete Order

If the buyer/seller decides to withdraw the order, the function can be called to clear information.

4. Delivery and settlement stage

- Pay To the Grid

According to the updated charging demand, all charging stations call the payment function of the smart contract to pay the grid company at a current standard market price during the delivery period. When the miner confirms the successful transaction transfer, the status variable of the charging station node address is updated to true, and the initial default value is false.

- Withdraw function

During the specified charging delivery period, the charging station should provide a charging service according to the results of the allocation of charging right. The charging power is fed back from the smart meter to the blockchain trading platform [43]. If the actual charging power is higher than the charging right, the state variable of the node address of the charging station is updated to false. The charging station can call the refund function of the smart contract to apply for the refund of the remaining margin. The miners confirm the application information. If the state variable is false (failing to pay to the power grid or failing to comply with the agreed quota of charging rights), the charging station refuses to pack the transaction into the blockchain and cannot retrieve the deposit. If true, the remaining margin can be recovered.

6. Examples and Analysis of Planning Results

6.1. The Setting of Simulation Parameters

The simulation scenario is set in a DN of 35 kV in Shanghai. The total rated capacity P_r of the transformer is 800 kVA, and the number of charging stations is 6. Assuming that the power factor $\cos\phi$ of the transformer is 0.85, and the efficiency η_t is 0.95, the maximum load P_{max} of the transformer can be calculated as 646 kW according to the following formula.

$$P_{max} = \eta_t P_{rc} \cos\phi \tag{17}$$

In this section, the exchange rate between Ether and CNY is set to be 1 eth = 1349 yuan, so the exchange rate between ET and Token is 1 eth = 1.349×10^5 token. This exchange rate can be modified by the grid company to achieve 1 yuan = 100 token. Specific parameters of the charge station purchasing power price from power grid are shown in Table 4.

6.2. Analysis of Simulation Results

In order to verify the validity of the mechanism, this section presents the allocated charging rights trading contract in Ethereum private-chain and builds a charging rights trading platform under the simulation scenario. The simulation parameters are shown in Table 4, and the simulation process is shown in Figure 3. The Ethereum account of each charging station is pre-deposited with 2×10^4 token before simulation. Below is a round of charging rights trading from 18:00–18:30. In the charging demand submission stage, each charging station submits the charging demand within 18:30–19:00 and pays the margin. The smart contract initially allocates charging rights for each charging station. The parameters are shown in Table 5.

Table 5. Parameters submitted by EV charging stations for charging demand.

Charging Station	Charging Requirements/(kW)	Initial Charging Right/(kW)	Margin/(Token)
A	48	40.38	5376
B	64	53.83	7168
C	56	47.10	6272
D	88	74.02	9856
E	40	33.65	4480
F	88	74.02	9856

Table 5 shows that the total charge demand submitted from 18:00–18:05 is 384 kW. Assuming that the conventional load accounts for half of the transformer's maximum load in this period, the remaining maximum charging load is 323 kW. The initial charging right can be calculated according to the charging demand satisfaction rate of each charging station.

In the double auction stage, A, C and F are the bidders of the seller. B, D and E are the bidders of the buyer. Among them, B, C, D and F complete the double auction transaction and settle through the blockchain. The bidding parameter of Ethereum is shown in Table 6.

Table 6. Parameters of the double auction.

Charging Station	Purchase Quantity/(kW)	Sale Quantity/(kW)	Quote/(Token/kW)
A	-	5.6	34
B	10.5	-	22
C	-	11.2	20
D	13.9	-	26
E	5.3	-	18
F	-	13.5	14

A's price is too high, and E is too low for the purchase price to match the right trader. After double matching, C still has the charge right of 0.3KW, and then the remaining bidding is transferred to the P2P trading stage to carry out the multilateral transaction. Double auction matching results are shown in Table 7.

Table 7. Transaction results of the double auction.

Charging Station	Transaction Price/(Token/kW)	Successful Bidder	Number of Winning Bids/(kW)	Bid Winning Income/(Token)	Balance/(kW)
A	-	-	-	-	5.6
B	21	C	10.5	−220.5	0
C	23 21	D B	0.4 10.5	9.2 220.5	0.3
D	20 23	F C	13.5 0.4	−270 −9.2	0
E	-	-	-	-	5.3
F	20	D	13.5	270	0

A lowered the quotation to 20 token/kW and issued a price limit order. E traded 5.3 kW at market price, while C abandoned trading and withdrew the order. In the P2P trading stage, the trading behavior and final results of A, C, E are shown in Table 8.

Table 8. Behaviors and results in the P2P period.

Charging Station	Transaction	Successful Bidder	Achieved Bid Volume/(kW)	Bid Winning Income/(Token)
A	Adjust the price to 20 token/kW and sell 5.6 kW	E	5.3	106
B	-	-	0	0
C	Remaining 0.3kW Withdrawal	-	0	0
D	-	-	0	0
E	Acquisition of 5.3kW at Market Price	A	5.3	−106
F	-	-	0	0

According to the charging right of the renewal, each charging station pays the electricity fee in the delivery period. The negative value of the settlement amount represents the expenditure of the charging station, and the positive value represents the income. F charging station fails to recover the remaining margin because the charging power is higher than the charging right quota. The final settlement results between charging stations and power grid are shown in Table 9.

Table 9. Monetary transfers and charging rights of EV charging stations.

Charging Station	Final Charging Right/(kW)	Power Grid Settlement/(Token)	Charging Rights Settlement/(Token)	Margin Refund/(Token)
A	35.08	−1964.5	106	3517.5
B	64.33	−3602.5	−220.5	3345
C	36.20	−2027.2	229.7	4474.5
D	87.92	−4923.5	−279.2	4653.3
E	38.95	−2181.2	-106	2192.8
F	60.52	−3389.1	270	0 (6736.9)

The six charging stations can submit charging demand and charging right quotations to the blockchain through the *geth* client of Ethereum. Based on the total charge demand, smart contracts (or miners who execute smart contracts) perform the following tasks in an automated, irrevocable manner. Tasks include allocation of charging rights, payment of margin, double matching and settlement, P2P transactions and settlement, real-time renewal of charging rights, grid settlement and margin refund. Blockchain ensures a secure and trusted transaction for charging right. At the same time, digital assets can be traded and settled through blockchains. Taking charging right as an economic incentive of digital assets can promote decentralized decision-making of charging stations, adjust charging demand and maximize benefits. For example, A, C and F independently choose to reduce the expected charging demand and sell the charging right. They obtained 106, 229.7 and 270 token, respectively. B, D and E choose to raise the expected charging demand and buy the charging right to meet the EVs charging demand in the delivery stage and achieve Pareto improvement.

As the number of transmitted messages increases, the communication overhead of the four methods increases linearly. By comparison, the overhead caused by sending the same number of messages is 34.55% of SPRING, 8.03% of IBCPPA and 30.39% of EAAP. Therefore, our method can save at least 63.45%, as shown in Figure 7.

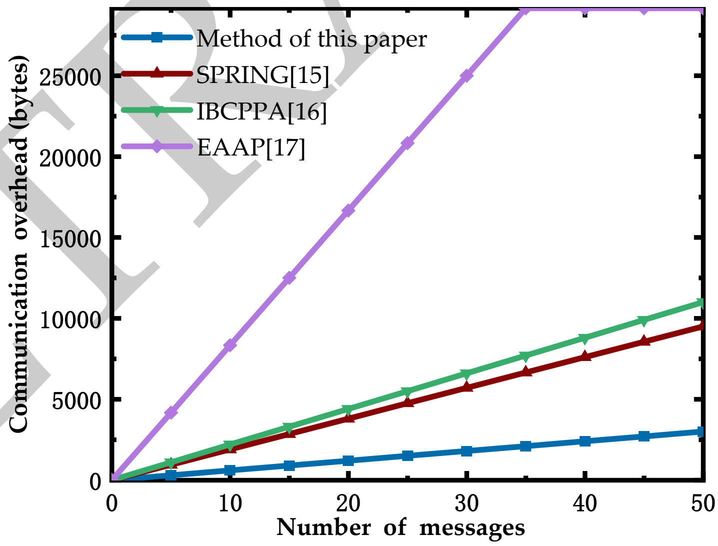

Figure 7. Communication overhead and the number of messages sent.

The electricity price reached by the smart contract is shown in Figure 8.

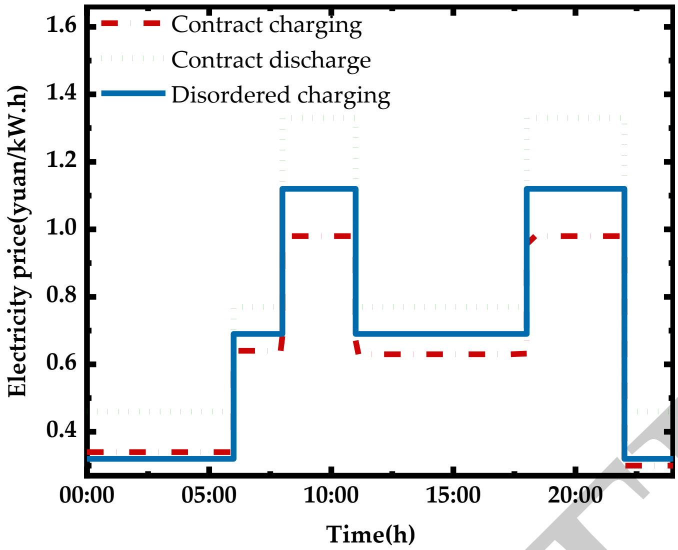

Figure 8. The electricity price reached by the smart contract.

The charging station mainly performs ordered charging control during the period of load and electricity price. Smart contracts reduce the price of disorderly charging to get the best return. During the low electricity consumption period, the charging station mainly performs charging control, and the optimized smart contract price is reduced overall; the discharge control is mainly performed during peak hours of load and electricity price, and a higher contract price is reached during the peak load period to obtain the optimum discharge benefits. The grid load curve after the optimal scheduling of the EV under the blockchain technology is shown in Figure 9.

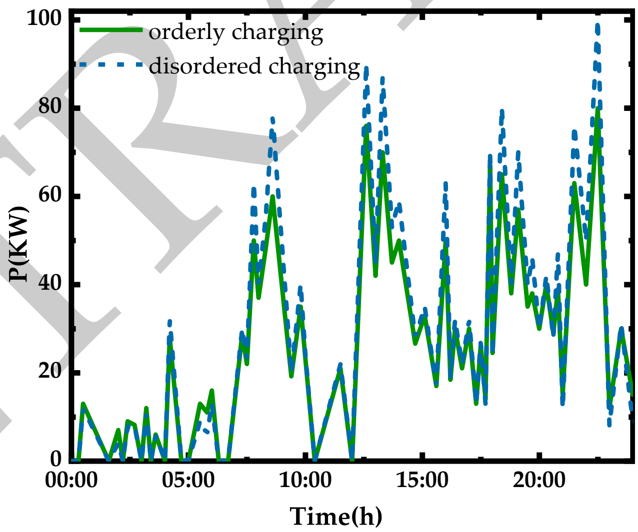

Figure 9. Load curve before and after disordered charging of EVs.

Disordered charging means that the EV immediately charges after reaching the charging station until the desired amount of charge is reached. However, after using the P2P technology of the blockchain, the peak and fluctuation of the load curve are reduced compared to the disordered charging. Blockchain technology can realize the semi-decentralized power trading of EVs and charging stations, ensuring that power transactions do not have a single point of failure, and can also protect user privacy and achieve reliable payment of charging costs.

Finally, this example follows the principle of "overall external constraints, internal autonomous coordination" to optimize the allocation of charging rights, and ensures that the transformer capacity does not exceed the limit while meeting the charging demand. The results show that the power limit of the transformer is 323 kW, and the total charging right is 323 kW. Social welfare is maximized when the capacity of the transformer is not limited. On the other hand, users who do not comply with the charging quota during the delivery period, such as charging station F, will be subject to financial penalties and cannot obtain the security deposit to maintain the safe operation of the DN.

7. Conclusions

Distributed energy has gradually become an important source of power generation by virtue of its characteristics of high energy efficiency, flexible operation and economy. The decentralization, openness and transparency of blockchain technology are consistent with the transaction demand of distributed energy. Exploring the blockchain-based distributed transaction mode can help to promote energy integration and reduce credit costs. Based on the Ethereum private-chain, this study designs and tests a trading method for charging right. The simulation results on the private-chain of blockchain show that:

1. The multilateral trading mechanism of charging rights based on the blockchain can meet the charging demand and the capacity limitation of the transformer.
2. Through the double auction, the double auction and P2P transaction rules designed make the part of the buyer's quotation no less than the seller's quotation match, and the rest of the quotations are listed in the P2P market to achieve Pareto improvement.
3. The trading platform based on the blockchain can ensure the transparency and survivability of trading mechanism, the security of settlement among participants, and solve the trust problem among users.
4. Optimizing the allocation of charging right. The research of blockchain in the field of power energy is still in its infancy.

The mobile characteristics of EVs and the decentralized deployment of charging stations constitute the P2P application mode. The rapid growth of private EVs urgently requires a secure and reliable charging transaction environment. Endurance makes charging a regular activity and places an urgent need on shared charging. With the support of the EV industry, the exploration of charging service innovation models has received more and more attention. The charging right combined with the blockchain, Ethernet and smart contract is a safe and reliable charging station sharing the trading environment, which will greatly facilitate charging users and improve the utilization rate of charging stations. This study focuses on the optimization of a single charging station. In the future, we will discuss the coordination optimization of charging stations and the interaction between other energy sources in an active DN and traditional network.

Author Contributions: All authors contributed to the research in the paper. X.Y. and W.S. conceived and designed the model. X.Z. and Z.W.provided the data. Z.S. analyzed the data. R.J. wrote the paper.

Funding: This work is supported by the National Natural Science Foundation of China (Grant Nos.51477099); National Natural Science Foundation of China Youth Fund (Grant Nos.61803253); Key Laboratory of Control of Power Transmission and Conversion (SJTU); and Ministry of Education (Grant Nos. 2016AB14).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Song, Y.; Yang, X.; Lu, Z. Integration of plug-in hybrid and electric vehicles: Experience from China. In Proceedings of the Power and Energy Society General Meeting, Providence, RI, USA, 25–29 July 2010; pp. 1–6.
2. Yuan, Z.; Hao, L.S. New Energy Policy Framework of the World and Its Forming Mechanism. *Resour. Sci.* **2005**, *27*, 62–69.
3. Awasthi, A.; Venkitusamy, K. Optimal Planning of Electric Vehicle Charging Station at the Distribution System Using Hybrid Optimization Algorithm. *Energy* **2017**, *133*, 70–78. [CrossRef]

4. Oda, T.; Aziz, M.; Mitani, T. Mitigation of Congestion Related to Quick Charging of Electric Vehicles Based on Waiting time and Cost-benefit Analyses: A Japanese Case Study. *Sustain. Cities Soc.* **2018**, *36*, 99–106. [CrossRef]
5. Dow, L.; Marshall, M.; Xu, L. A novel approach for evaluating the impact of electric vehicles on the power distribution system. In Proceedings of the Power and Energy Society General Meeting, Providence, RI, USA, 25–29 July 2010; pp. 1–6.
6. Staats, P.T.; Grady, W.M.; Arapostathis, A. A procedure 11 for derating a substation transformer in the presence of widespread electric vehicle battery charging. *IEEE Trans. Power Deliv.* **1997**, *12*, 1562–1568. [CrossRef]
7. Aljanad, A.; Mohamed, A.; Shareef, H. A novel method for optimal placement of vehicle-to-grid charging stations in distribution power system using a quantum binary lightning search algorithm. *Sustain. Cities Soc.* **2018**, *38*, 174–183. [CrossRef]
8. Sortomme, E.; Hindi, M.M.; MacPherson, S.D.J. Coordinated charging of plug-in hybrid electric vehicles to minimize distribution system losses. *IEEE Trans. Smart Grid* **2011**, *2*, 198–205. [CrossRef]
9. Dharmakeerthi, C.H.; Mithulananthan, N.; Saha, T.K. Modeling and planning of EV fast charging station in power grid. In Proceedings of the IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012; pp. 1–8.
10. Xie, F.X.; Huang, M.; Zhang, W.G. Research on Electric Vehicle Charging Station Load Forecasting. In Proceedings of the International Conference on Advanced Power System Automation & Protection, Beijing, China, 16–20 October 2011.
11. Wang, J.; Wu, K.H.; Wang, F. Electric Vehicle Charging Station Load Forecasting and Impact of the Load Curve. *Appl. Mech. Mater.* **2012**, *229*, 853–858. [CrossRef]
12. Louie, H.M. Probabilistic Modeling and Statistical Analysis of Aggregated Electric Vehicle Charging Station Load. *Electr. Mach. Power Syst.* **2015**, *43*, 2311–2324. [CrossRef]
13. Yang, S.; Wu, M.; Jiang, J. An Approach for Load Modeling of Electric Vehicle Charging Station. *Power Syst. Technol.* **2013**, *37*, 1190–1195.
14. Huang, X.; Chen, J.; Chen, Y. Load Forecasting Method for Electric Vehicle Charging Station Based on Big Data. *Autom. Electr. Power Syst.* **2016**, *12*, 68–74.
15. Lu, R.; Lin, X.; Shen, X. Spring: A Social-based Privacy-preserving Packet Forwarding Protocol for Vehicular Delay Tolerant Networks. In *Conference on Information Communications*; IEEE Press: San Diego, CA, USA, 2010; pp. 1229–1237.
16. Shao, J.; Lin, X.; Lu, R. A Threshold Anonymous Authentication Protocol for VANETs. *IEEE Trans. Veh. Technol.* **2015**, *65*, 1711–1720. [CrossRef]
17. Azees, M.; Vijayakumar, P.; Deboarh, L.J. EAAP: Efficient Anonymous Authentication With Conditional Privacy-Preserving Scheme for Vehicular Ad Hoc Networks. *IEEE Trans. Intell. Transp. Syst.* **2017**, *18*, 2467–2476. [CrossRef]
18. Kang, J.; Rong, Y.; Huang, X. Enabling Localized Peer-to-Peer Electricity Trading Among Plug-in Hybrid Electric Vehicles Using Consortium Blockchains. *IEEE Trans. Ind. Inform.* **2017**, *13*, 3154–3164. [CrossRef]
19. Dinh, T.T.A.; Rui, L.; Zhang, M. Untangling Blockchain: A Data Processing View of Blockchain Systems. *IEEE Trans. Knowl. Data Eng.* **2018**, *30*, 1366–1385. [CrossRef]
20. Masiello, R.; Aguero, J.R. Sharing the ride of power understanding transactive energy in the ecosystem of energy economics. *IEEE Power Energy Mag.* **2016**, *14*, 70–78. [CrossRef]
21. Sidhu, J. Syscoin: A Peer-to-Peer Electronic Cash System with Blockchain-Based Services for E-Business. In Proceedings of the International Conference on Computer Communication & Networks, Allahabad, India, 24–26 November 2017.
22. Wang, A.P.; Fan, J.G.; Guo, Y.L. Application of Blockchain in Energy Interconnection. *Electr. Power Inf. Commun. Technol.* **2016**, *9*, 1–6.
23. Kim, M.; Song, S.; Jun, M.S. A study of blockchain-based peer-to-peer energy loan service in smart grid Environments. *Adv. Sci. Lett.* **2016**, *22*, 2543–2546. [CrossRef]
24. Li, S. Application of Blockchain Technology in Smart City Infrastructure. In Proceedings of the 2018 IEEE International Conference on Smart Internet of Things (SmartIoT), IEEE Computer Society, Xi'an, China, 17–19 August 2018; pp. 276–2766.

25. Yue, X.; Liu, J.; Ran, L. Economic planning of electric vehicle charging stations considering traffic constraints and load profile templates. *Appl. Energy* **2016**, *178*, 647–659.
26. Deng, B.; Wang, Z. Research on Electric-Vehicle Charging Station Technologies Based on Smart Grid. In Proceedings of the Power & Energy Engineering Conference, Washington, DC, USA, 25–28 March 2011.
27. Li, Y.; Ling, L.; Jing, Y. Layout Planning of Electrical Vehicle Charging Stations Based on Genetic Algorithm. *Lect. Notes Electr. Eng.* **2011**, *99*, 661–668.
28. Liu, Z.; Zhang, W.; Wang, Z. Optimal Planning of Charging Station for Electric Vehicle Based on Quantum PSO Algorithm. *Proc. CSEE* **2012**, *32*, 39–45.
29. Hu, X.; Martinez, C.M.; Yang, Y. Charging, power management, and battery degradation mitigation in plug-in hybrid electric vehicles: A unified cost-optimal approach. *Mech. Syst. Signal Process.* **2017**, *87*, 4–16. [CrossRef]
30. van Roy, J.; Leemput, N.; Geth, F. Electric Vehicle Charging in an Office Building Microgrid with Distributed Energy Resources. *IEEE Trans. Sustain. Energy* **2014**, *5*, 1389–1396. [CrossRef]
31. Pasetti, M.; Rinaldi, S.; Flammini, A.; Longo, M.; Foiadelli, F. Assessment of Electric Vehicle Charging Costs in Presence of Distributed Photovoltaic Generation and Variable Electricity Tariffs. *Energies* **2019**, *12*, 499. [CrossRef]
32. Matzner, M.; Chasin, F.; Hoffen, M.V. Designing a Peer-to-Peer Sharing Service as Fuel for the Development of the Electric Vehicle Charging Infrastructure. In Proceedings of the 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, USA, 5–8 January 2016.
33. Plenter, F.; Chasin, F.; von Hoffen, M. Assessment of peer-provider potentials to share private electric vehicle charging stations. *Transp. Res. Part D Transp. Environ.* **2018**, *64*, 178–191. [CrossRef]
34. Zhumabekuly, A.N.; Svetinovic, D. Security and Privacy in Decentralized Energy Trading through Multi-signatures, Blockchain and Anonymous Messaging Streams. *IEEE Trans. Dependable Secur. Comput.* **2016**, *15*, 840–852.
35. Kosba, A.; Miller, A.; Shi, E. Hawk: The Blockchain Model of Cryptography and Privacy-Preserving Smart Contracts. In Proceedings of the IEEE Symposium on Security and Privacy, San Jose, CA, USA, 22–26 May 2016.
36. Christidis, K.; Devetsikiotis, M. Blockchains and Smart Contracts for the Internet of Things. *IEEE Access* **2016**, *4*, 2292–2303. [CrossRef]
37. Plenter, F. Eliciting Value Propositions and Services in the Market for Electric Vehicle Charging. In Proceedings of the IEEE 19th Conference on Business Informatics (CBI), Thessaloniki, Greece, 24–27 July 2017.
38. Marc, P. *Blockchain Technology: Principles and Applications*; Social Science Electronic Publishing: Rochester, NY, USA, 2015.
39. Li, X.; Peng, J.; Chen, T. A Survey on the security of blockchain systems. *Future Gener. Comput. Syst.* **2017**. [CrossRef]
40. Watanabe, H.; Fujimura, S.; Nakadaira, A. Blockchain contract: Securing a blockchain applied to smart contracts. In Proceedings of the IEEE International Conference on Consumer Electronics (ICCE), Las Vegas, NV, USA, 1–7 January 2016; pp. 467–468.
41. Alam, M.T.; Li, H.; Patidar, A. Bitcoin for smart trading in smart grid. In Proceedings of the IEEE International Workshop on Local and Metropolitan Area Networks, Beijing, China, 22–24 April 2015; pp. 1–2.
42. Wang, S.; Ouyang, L.; Yuan, Y. Blockchain-Enabled Smart Contracts: Architecture, Applications, and Future Trends. *IEEE Trans. Syst. Man Cybern. Syst.* **2019**, 1–12. [CrossRef]
43. Valtanen, K.; Backman, J.; Yrjölä, S. Blockchain-Powered Value Creation in the 5G and Smart Grid Use Cases. *IEEE Access* **2019**, *7*, 25690–25707. [CrossRef]