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EV charging coordination via blockchain-based charging power quota trading

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***Abstract*—With the increasing electric vehicle (EV) integration, challenges arise in the operation of a distribution network in that charging numerous EVs at the same time may overload distribution facilities. The charging power should be distributed among the charging stations in such a way that both individual EV charging demands and security constraints are met. Meanwhile, there usually does not exist a coordinator over all EV charging stations. This paper proposes an EV charging coordination method by designing a charging power quota (permissible charging power of a charging station) trading platform on blockchain. After collecting the future charging demands from charging stations, the proposed platform distributes initial charging power quotas in an equitable and secure manner while considering facility ratings. Then, considering the elasticity of different charging stations, the platform allows EV charging stations to trade the initially-allocated charging power quota via a double auction. By matching the submitted offers and bids from charging stations, the optimal allocation of charging power quotas is realized. By designing corresponding smart contracts, a charging power quota allocation and trading platform is established based on the Ethereum blockchain, ensuring the transparency, trustfulness, and intelligence of the charging power quota trading. A case study based on an Ethereum private blockchain shows the fairness and efficiency of the proposed mechanism and the effectiveness of the method.**

***Index Terms*—Blockchain, smart contract, double auction, charging power quota**

I. Introduction

A. Motivation

Increasing EV penetration brings potential challenges to the secure operation of a distribution network. One of challenges is that simultaneous EV charging may result in overloads of distribution-side facilities [1]. Hence it is a key issue to design an effective EV charging coordination mechanism. To this end, an EV charging coordinator is necessary to enable this but unfortunately in practice, such a coordinator may not exist. This paper aims to address these two issues, i.e., how to meet individual EV charging preferences while considering security constraints, and how to achieve this given the absence of a central coordinator.

B. First contribution

There are remarkable studies on coordinating EV charging stations. In some researches, a central operator collects charging demands of all charging stations (or all EVs) and optimizes the charging schedules while considering system constraints [1]–[5]. However, centralized optimization becomes impractical with a huge number of integrated EVs. To release the computational burden of the central operator, decentralized methods are introduced to the charging coordination problem [6]–[8]. The optimal charging schedule is achieved through iterations between the central coordinator and all charging stations (or all EVs). Though these methods significantly reduce the computational cost of the coordinator, frequent communication between the coordinator and charging stations is needed, which may be impractical.

Our first contribution is to propose a two-stage EV charging coordination mechanism. The permissible charging power of a charging station is represented by charging power quotas. At the first stage, the charging power quotas are initially allocated in an equitable and secure manner. At the second stage, the charging power quota trading is enabled via a double auction. Charging stations with elastic demand can sell charging power quotas to charging stations with inelastic demand. This yields the pareto optimal allocation of charging power quotas.

C. Second contribution

To organize the charging power quota trading among charging stations, a reliable coordinator is indispensable. Recently,

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blockchain technology is introduced to the power grid [9], [10]. On blockchain, the energy trading can be organized without a central coordinator. The fairness and correctness of the trading is guaranteed by cryptography, ensuring trustful, decentralized, and transparent operation. Hence, blockchain is fit for the coordinator of charging stations. Study [11] enables local P2P electricity trading between EVs in a charging station to maximize the total welfare of all parking EVs. In [12], the demand fluctuation level is reduced by running an iceberg order algorithm on blockchain. Study [13] satisfies EVs individual needs by designing a smart contract. However, in these studies, the security of distribution facilities is rarely considered.

Our second contribution is to implement the proposed coordination mechanism on blockchain. The charging power quota is a typical digital asset, which is suitable for trading and settlement on blockchain. A decentralized, trustful, and transparent double-auction-based charging power quota trading platform is enabled by designing a smart contract. Simulation on an Ethereum private chain verifies the effectiveness of the proposed mechanism and our trading platform on blockchain.

II. EV CHARGING POWER QUOTA TRANSACTION MECHANISM

In this paper, the EV charging schedules are coordinated in a two-layer structure. The lower layer is the EV charging station layer. A charging station collects the battery statuses and the charging demands of EVs, and charges integrated EVs according to the allocated charging power quota. The upper layer is the coordinator layer. The charging power quotas are coordinated and allocated to charging stations to maximize overall welfare.

The proposed EV charging power quota transaction mechanism features two stages:

At the first stage, the distribution system operator (DSO) forecasts the conventional load and calculates the capacity margin of facilities, e.g., the transformer at the T-D station. At the same time, each charging station submits its charging demand. If the summation of the charging demand of all charging stations doesn't exceed the capacity margin, all demands can be met. Otherwise, the capacity margin is distributed to charging stations according to the proportion of the submitted demand of each charging station. At this stage, the charging power quotas are allocated equitably whereas the difference of charging urgency across charging stations is ignored.

At the second stage, charging stations can trade their charging power quotas with each other through a double auction. Charging stations with inelastic demand have strong willingness of charging, so they are buyers in the double auction market. In contrast, charging stations with elastic demand are sellers in the market. By matching the submitted bids and offers from charging stations, buyers meet the inelastic charging demand, whereas sellers receive profits by selling charging power quotas. This yields Pareto improvement.

We divide a day into 48 periods. In each period, the charging power quotas in the next period will be allocated and traded. For example, energy delivered in 18:30-19:00 is traded in 18:00-18:30. It is detailed below.

Step 1: At 18:00, the DSO calculates and broadcasts the capacity margin of the transformer at the T-D station during 18:30-19:00 according to conventional load forecast.

Step 2: In 18:00-18:05, all charging stations submit their charging demand in 18:30-19:00 by collecting the charging demands of on-site EVs.

Step 3: In 18:05-18:07, a charging demand satisfaction rate β is calculated by (1).

$$\beta = \begin{cases} 1, & \sum_{i\in\Omega_{\mathrm{E}}} P_i \leq \mathrm{P_M} \\ \mathrm{P_M} / \sum_{i\in\Omega_{\mathrm{E}}} P_i, & \sum_{i\in\Omega_E} P_i > \mathrm{P_M} \end{cases} \tag{1}$$

where $\mathrm{P_M}$ is the capacity margin of the transformer in the next period broadcast by the DSO. Ω_{E} is the set of charging stations. P_i is the charging charging demand of station i.

The initial charging power quotas of stations are determined by β. If the total charging demand is less than the capacity margin, the allocated charging power quota of each station during 18:30-19:00 is equal to its submitted demand and the following steps are skipped. Otherwise, to avoid the overload of the transformer, the initial charging power quota of each station is calculated in (2).

$$P_i^{init} = \beta P_i \tag{2}$$

where P_i^{init} is the initial charging power quota distributed to station i.

Step 4: After all charging stations get the initial charging power quotas, in 18:07-18:10, all stations can evaluate the elasticity of the charging demand and then submit the quantity and the price of charging quota they are willing to purchase from/ selling to other stations.

Step 5: In 18:10-18:15, bids and offers from charging stations are cleared based on the double auction mechanism. The mechanism is illustrated in Fig. 1. Firstly, the mechanism orders the bids/ offers from buyers/ sellers. Secondly, the mechanism matches bids and offers orderly until the highest bid is lower than the lowest offer. Clearing prices are the average of bids and offers. For example, in Fig. 1, clearing prices are illustrated by the red line. Bids and offers on the left side of the dashed line are cleared. After the charging power quota trading market is cleared, all stations will be settled and their charging power quotas will be updated according to the transaction results.

Step 6: In 18:30-19:00, charging stations charge the on-site EVs according to the final charging power quotas. And all charging stations pay the charging fees to the DSO. The actual charging load is monitored by smart meters and sent to the DSO. If the actual charging load is higher than the charging power quota, the station will be penalized because it disturbs the secure and stable operation of the distribution network.

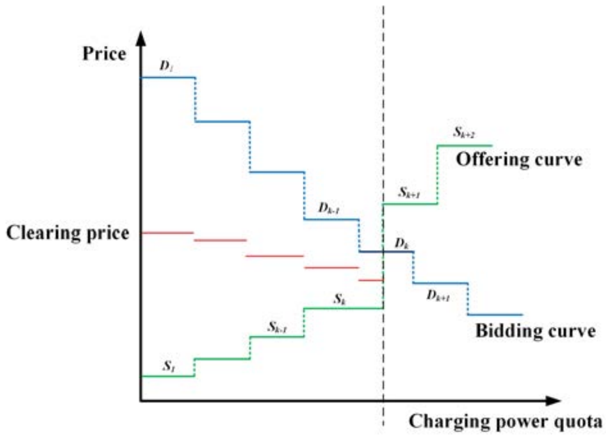

Fig. 1. Double auction mechanism of the charging power quota

III. Implementation via Ethereum

To build a trustful, transparent, and decentralized trading platform, we implement the proposed mechanism on Ethereum by designing a corresponding smart contract. The coordination processes are divided into three procedures including charging demand submission, charging power quota double auction, and settlement. Fig. 2 provides a flowchart of the charging power quota trading on Ethereum. The details of the associated functions are explained as follows.

A. Charging demand submission

1) *Initialize*.

The *Initialize* function, referring to step 1 in Section II, can be only called by the DSO at the beginning of the trading period. With this function, the currency exchange rate for Ether to the Token in the smart contract, the real-time electricity price, and the capacity margin of the transformer are updated. Due to the fluctuation of Ether's value, we choose the ERC-20 Token as the payment currency. By modifying the currency exchange rate for Ether to the Token, a Token is always worth 0.01 CNY. In the rest part of this section, the Token is the unit of the price.

2) *Demand_submit*

The *demand_submit* function refers to step 2 in Section II. By calling this function before the deadline of the charging demand submission procedure, charging stations submit the charging demands for the next period to the smart contract. When calling this function, stations must pay deposits to the contract.

The deposits paid by charging stations has the following purposes. Firstly, part of deposits will be used in the double auction market for the settlement of charging power quotas. Secondly, deposits contain the charging fees that will be paid to the DSO. Thirdly, a penalty will be deducted from deposits if the actual power consumption of charging stations is more than their charging power quotas.

3) *Pre-allocation*

The *pre-allocation* function refers to step 3 in Section II. By executing this function, the smart contract distributes the initial charging power quotas by (1) and (2). If the total charging demand doesn't exceed the capacity margin of the transformer, procedure 2 will be skipped. Otherwise, the smart contract will trigger the double auction market. By monitoring the contract, charging stations can view their initial charging power quotas and the time when the double auction starts.

B. Charging power quota double auction

1) *Submit*

The *submit* function refers to step 4 in Section II. When the double auction market is triggered, charging stations can submit the purchase/ selling prices of charging power quotas by calling this function. The smart contract will sort bids/ offers in a descending/ ascending order.

2) *Auction*

The *auction* function refers to step 5 in Section II. After the deadline of submission, the bids and offers are matched in the double auction market after the DSO calls this function. The detail of the algorithm is shown in Algorithm 1.

Algorithm 1 charging power quota double auction

Sort of bids in a descending order:
$bids = \{(bid_1, demand_1), ..., (bid_n, demand_n)\}$
Sort of offers in an ascending order:
$offers = \{(offer_1, supply_1), ..., (offer_m, supply_m)\}$
while $bids! = \{\}$ & $offers! = \{\}$ & $bid_1 \geq offer_1$ **do**
    $price = (bid_1 + offer_1)/2$
    $amount = min(demand_1, supply_1)$
    transaction(from: $buyer_1$, to: $seller_1$, value: $price * amount$)
    $(bid_1, demand_1) \leftarrow (bid_1, demand_1 - amount)$
    $(offer_1, supply_1) \leftarrow (offer_1, supply_1 - amount)$
    if $demand_1 == 0$ **then**
        for $(bid_i, demand_i) \in bids$ **do**
            $(bid_i, demand_i) \leftarrow (bid_{i+1}, demand_{i+1})$
        end for
    else
        for $(offer_j, supply_j) \in offers$ **do**
            $(offer_j, supply_j) \leftarrow (offer_{j+1}, supply_{j+1})$
        end for
    end if
end while

C. Settlement

1) *Payment*

After energy delivery, all charging stations must pay the DSO for the charging services by calling this function. The values of the payments depend on the pre-determined tariff and the actual energy consumption measured by smart meters.

2) *Withdraw*

With this function, charging stations who have already called the *payment* function can withdraw the rest of the deposits. Moreover, the deposits will compensate the DSO if the actual energy consumption of charging stations is higher than their charging power quotas. This is also a penalty for

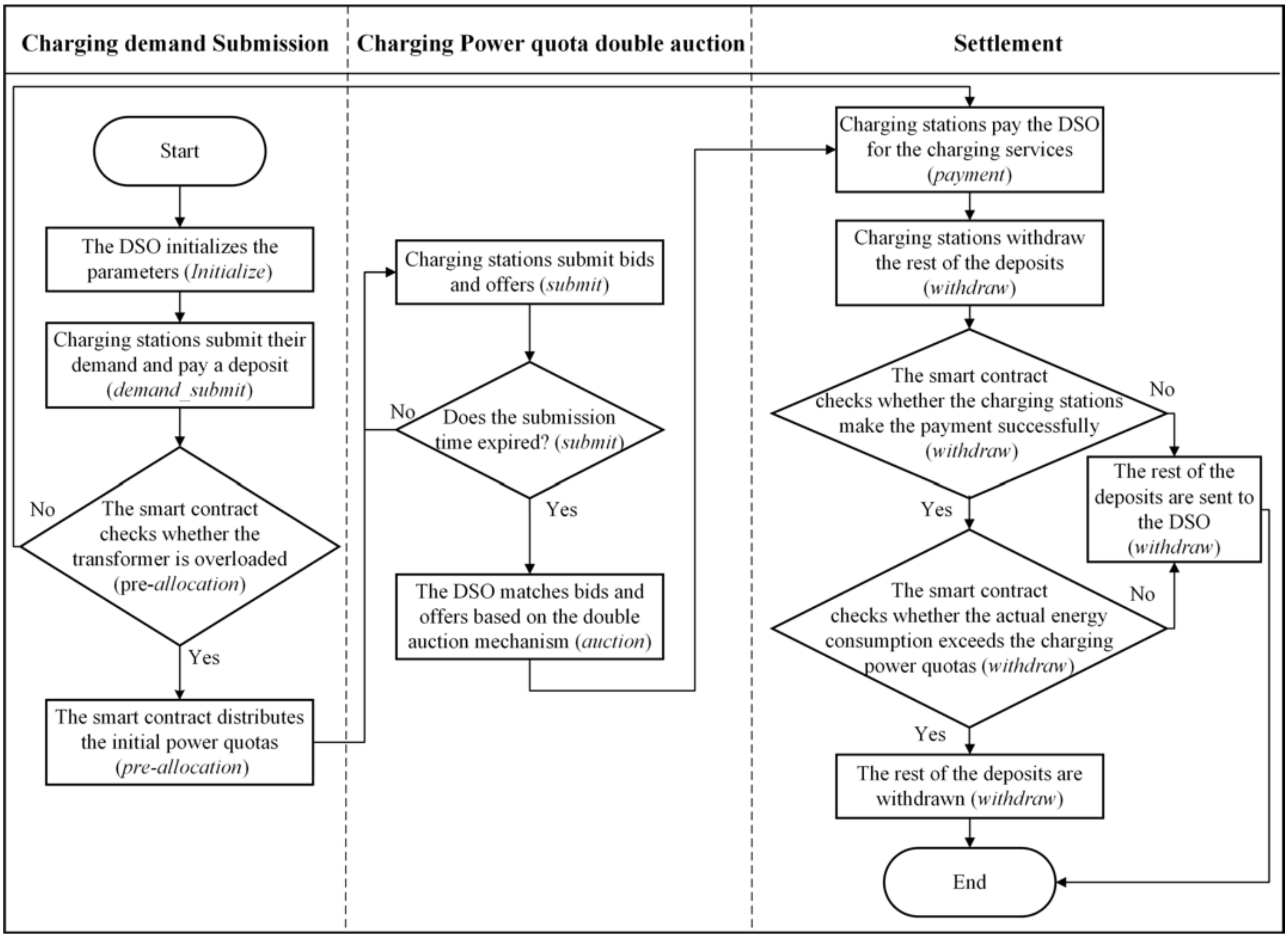

Fig. 2. Flowchart of charging power quota trading on Ethereum

the station in default. This function, together with the *payment* function constitutes step 5 in Section II.

IV. Case studies

A. Data

A case study is done on a distribution network under a 10-kV transformer in Shanghai. It is assumed that the capacity margin of the transformer is 343 kW. The real-time electricity prices are shown in table I. We simulate the charging power quota trading in 18:00-18:30 on an Ethereum private chain. 8 charging stations participate the charging power quota trading, named as A - H. The charging demands are simulated by the Monte-Carlo method.

TABLE I
Real-time electricity prices

Time	Electricity price (RMB/kWh)	Electricity price (Token/kWh)
22:00-6:00	0.32	32
8:00-11:00 18:00-22:00	1.12	112
6:00-8:00 11:00-18:00	0.69	69

B. Simulation results

In the charging demand submission procedure, firstly, the DSO calls the *initialize* function and charging stations call the *demand_submit* function. Then, by executing the *pre-allocation* functions, the allocation scheme of initial charging power quotas is shown in table II. The total charging demand of all charging stations is 390kW. Therefore, the charging demand satisfaction rate $\beta = 0.83$.

In the charging power quota double auction market, the submitted bids and offers of charging stations are shown in table III. After the DSO calls the *auction* function, all participants can view the the result of the double auction market from the blockchain, which is illustrated in Fig. 3.

In the settlement procedure, all charging stations pay the DSO and withdraw deposits. As a result, the changes of balances of charging stations are shown in table IV, where

TABLE II
ALLOCATION SCHEME OF INITIAL CHARGING POWER QUOTAS

Charging station	Charging demand (kW)	Initial charging power quota (kW)
A	36	29.82
B	48	39.75
C	42	34.78
D	66	54.66
E	30	24.85
F	66	54.66
G	54	44.72
H	48	39.75

TABLE III
BIDS AND OFFERS OF CHARGING STATIONS IN THE DOUBLE AUCTION MARKET

Charging station	Demand (kWh)	Supply (kWh)	Unit price (Token/kWh)
A	/	3.2	25
B	6.5	/	24
C	/	9.8	22
D	10.9	/	26
E	3.2	/	28
F	/	7.2	19
G	5.4	/	20
H	/	6.8	16

the minus payment represents an income.

The simulation results show that Ethereum can effectively coordinate charging stations. By interacting with the smart contract deployed on the Ethereum private chain, charging stations receive charging power quotas in a transparent and decentralized way. And as a digital asset, charging power quotas can be conveniently settled on Ethereum.

In the charging power quota trading simulation, except charging station A and G, other charging stations either receive profits by selling charging power quotas, or satisfy their inelastic charging demand. Therefore, with the proposed mechanism, all participants can make Pareto improvement while the system security constraint is satisfied.

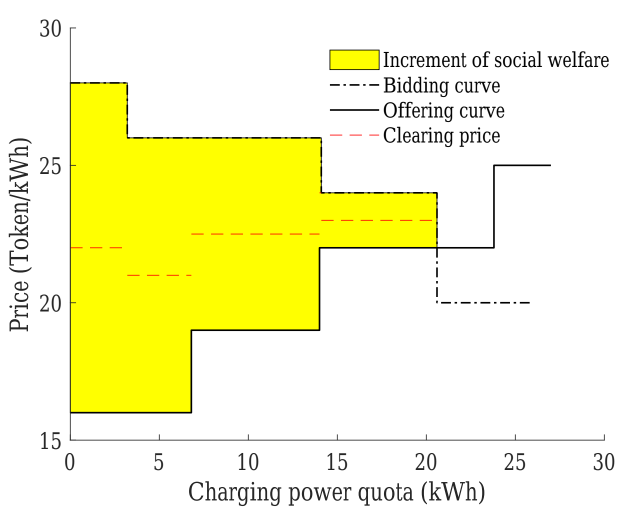

Fig. 3. Result of the charging power quota trading

TABLE IV
SETTLEMENT OF THE CHARGING STATIONS

Charging station	Charging service fee (Token)	Payment in double auction (Token)
A	3339.32	0
B	4452.43	73.6
C	3895.88	-225.4
D	6122.09	250.7
E	2782.77	73.6
F	6122.09	-165.6
G	5008.98	0
H	4452.43	-156.4

V. CONCLUSION

This paper proposes a two-stage EV charging coordination method. In the proposed method, the charging power is allocated to charging stations in a secure, fair, and efficient way. The following charging power quota trading method enables charging stations to make Pareto improvement. Given the lack of a central coordinator, the proposed mechanism is implemented via the Ethereum blockchain. Transparency and effectiveness of the coordination are guaranteed by the blockchain technology.

The simulation results show the effectiveness of the proposed coordination method. One can also see that the designed platform on Ethereum can efficiently coordinate charging stations, providing a practical solution with the absence of central coordinators in practice.

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