A Smart Contract-based Energy Trading Strategy in Energy Internet

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***Abstract*—Energy Internet (EI) aims at establishing a fast, credible, automated energy transaction pattern between suppliers and consumers to help both build and execute transactions efficiently. As a decentralized and distributed accounting mode, blockchain technology fits the requirements of automated energy trading in EI. Corresponding to the transaction principle, an smart contract-based energy trading strategy is proposed, which divides the trading process into three stages: the order submission stage, the matchmaking trading stage and the transaction execution stage. In our approach, the energy transaction can be executed automatically just need the submitted supply orders and demand orders. The transactions among the electricity market participants is used as a example to explain the details of the trading process. Finally, the smart contracts of the transactions are designed and deployed on Hyperledger Fabric (HLF) to demonstrate the validity of the proposed transaction strategy. And a trading strategy analysis is given.**

Keywords*—energy trading, blockchain, Hyperledger Fabric, energy Internet, smart contract

I. INTRODUCTION

As conventional energy sources become increasingly exhausted, more and more organizations have begun to pay attention to various new energy research [1], [2]. New technologies such as wind energy and solar energy with relatively mature technologies are geographically dispersed, poor level of operation management, low efficiency of energy utilizing and high energy conversion cost. Those problems make new energy resources greatly restricted in large-scale application and marketization promotion. In recent years, the energy Internet (EI) represented by “new energy + Internet” has become the new frontier of scientific and technological innovation in the international energy academic community and industry. It is another important development direction in the energy field after the smart grid.

EI focuses on the power system and bases on the Internet and other cutting-edge information technologies, using distributed renewable energy as the primary energy source, and other systems such as natural gas networks and transportation networks as a new energy utilization system. EI will connect massive distributed devices (distributed generation equipment, energy storage equipment, smart appliances and electric vehicles, etc.), large-scale users and integration of various energy networks [3]. At present, the United States, Germany, Switzerland, Japan and many other countries have begun to carry out research and development of the EI, involving the network framework, key technical equipment, demonstration pilot projects and other aspects. The US FREEDM research project puts forward the concept of EI from the perspective of distributed energy supply in distribution networks [4]. Japan focuses on the development of the digital power grid system. Japan Digital Grid Alliance has proposed an EI based on “power routers” [5].

Energy autonomous units such as Microgrids (MGs) and distributed energy can be used as the basic elements of the EI [6]. They can form local area networks through energy generation, micro energy collection, convergence and sharing, and energy storage or power consumption in MGs [7]. Some research works have been carried out regarding energy management. In [8], an optimal energy management strategy for EI through deep reinforcement learning approach is presented. In [9], real and reactive power management strategies of electronically interfaced distributed generation (DG) units in the context of a multiple-DG MGs system are proposed. An optimal and robust control method in an island MGs system is proposed in [10]. In [11], a multi-objective capacity configuration optimization model for the island microgrid with wind/photovoltaic/diesel/storage and seawater desalination load has been proposed. In consideration of transmission losses and the directed information flow, a consensus-based distritbuted energy management strategy for distributed generation units and response demands is proposed in [12]. Study [13] concentrates on coordinated frequency control among multiple microgrids in EI. In both [14] and [15], the authors maily focus on hybrid energy system and global optimization. Considering the energy system robustness and operation cost optimization, some control strategies are proposed by researchers [16], [17]. Current research related to peer-to-peer (P2P) distributed energy trading include demand response optimization, power routing, network communication, security and privacy. A number of projects and trails in energy sector have significantly increased recently all around the world. In [18], the authors elaborate some focuses and outcomes of energy trading projects, and compares their similarities and differences. In [19], a comprehensive survey of existing demand response optimization models, power routing devices and power routing algorithms are presented. A design of mixed H_2/H_∞ controller for an energy router within the scenario of EI is presented in [20].

Thereafter, blockchain as a decentralized, P2P trusted network is the core support technology of digital cryptographic currency system represented by Bitcoin [21], [22]. The nodes in blockchain network do not need to trust each other by utilizing data encryption, timestamp, distributed consensus, and economic incentives. Blockchain provides a solution for the problems of high cost, low efficiency, and insecure data storage that exist in centralized organizations [23], [24]. A systematic review of blockchain activities and initiatives in the energy sector is provided [25], which included a overview of key principles of distributed ledger technologies, detailed review of energy applications and use cases such as P2P energy trading. Discussion on benefits and limitations of blockchains for energy applications and review and classification of around 140 blockchain commercial and research initiatives are presented. In EI, the basic goal is to keep a balance between energy supply and demand in an efficient and secure way [26], [27]. A game theoretic model for demand side management that incorporates storage components is presented in [28], wherein, the supply constraints in the form of power outages are taken into account by the proposed model. In [29], the authors present the concept of a blockchain-based microgrid energy market as well as a framework with seven market components and evaluate the Brooklyn Microgrid project as a use case according to the required components. In [30], the authors propose a decentralized solution based on Ethereum for managing demand response programs in the context of smart grids and integrate the elements of the grid with a blockchain architecture. The validated and tested results of blockchain-based decentralized management system are promising, showing that the grid is capable of timely adjustments of the energy demand in near real time based on blockchain technology. Corresponding to the transaction principle, a blockchain-based integrated energy transaction mechanism has been proposed in [31], explaining the details of the trading process with the transactions among the electricity and heat market participants as examples. In addition, the smart contracts of the transactions are designed and deployed on Ethereum private blockchain to verify the effectiveness of the proposed transaction scheme. In [32], a shared control through smart contract in decentralized energy systems has been proposed, wherein, shared control of a power-electronic-based DC-link is chosen as the control element.

This study applied blockchain to the P2P energy trading, and a smart contract-based energy trading strategy is proposed, dividing the trading process into three stages: the order submission stage, the matchmaking trading stage and the transaction execution stage. We designed the smart contracts of the sellers' energy supplys, the buyers' demands, the trading matchmaking, and the trading settlement, which are deployed on Hyperledger Fabric (HLF) [33], [34], which is a enterprised blockchain platform. The importance and contribution of this paper can be highlighted as follows.

- A new P2P energy trading strategy is proposed for a generalized EI system. The energy transaction can be executed automatically as long as the submitted supply orders match with the demand orders. This kind of strategy has not been developed in previous study to the authors' knowledge.
- The smart contracts of the energy transactions are designed and deployed on HLF to demonstrate the validity of the proposed transaction strategy.
- At present, most decentralized energy trading models are based on a permissionless blockchain platform Ethereum. The considered platform in this paper is HLF, which is a permissioned blockchain platform with more security and flexibility.

The rest of the paper is organized as follows. an energy trading strategy based on smart contract is given in Section II. The formulation of the smart contract is presented in Section III. Section IV presents a simple case study, aimed at validating the trading strategy proposed. Finally, section 4 provides the conclusion of our work.

II. Energy Trading Strategy in EI

In this section, we propose a P2P energy trading strategy based on smart contract. The process diagram of the transactions is shown in Fig. 1. State database options include LevelDB and CouchDB. CouchDB additionally enables rich query not just key-value store. LevelDB is the default state database and stores chaincode data as simple key-value pairs. In this paper, we focus on the design of smart contract. We assume each user has a blockchain account. And smart meters are available to upload power data to the blockchain network. An energy usage plan should be determined one day in advance, which means the delivery time is the next day.

Figure 1. Process diagram of the transactions

The transaction process proposed in this paper is divided into three stages: the order submission stage, matchmaking trading stage and transaction execution stage. The strategy divides time into terms of specific length, as shown in Fig. 2. There are 9 terms in each day from 9:00 a.m. to 6:00 p.m.. In the earlier 50 minitues in one term, it is the orders submission time. In the last 10 minutes, it is the matchmaking trading time. In this paper, the transaction price is determinted by the buyer and seller. The pricing mechanism is different from existing dynamic pricing mechanism [35].

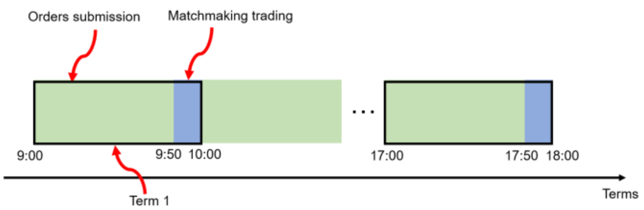

Figure 2. The period of energy trading strategy

A. *The Order Submission Stage*

The sellers and buyers make supply orders or demand orders and then submit the orders on the smart contract. The order contains the seller's or buyer's account addrees, the delivery time, the sign, the energy amount, the energy price and the state. Each user has the unique account address. It can be indicated by hexadecimal notation. The delivery time means the trading period with a one-hour interval. The sign is 0 or 1, 0 is for seller and 1 is for buyer. A seller and a buyer only can trade energy with each other within the same trading period. For sellers, the price is the lowest desired selling price. It is the highest desired buying price to the buyers. The energy amount is the seller's or buyer's expected trading volume. The state means the seller and buyer whether the matchmaking trading has completed, 0 is for the initial state. After the orders being submitted, these data will be stored in the state database such as CouchDB.

B. *The Matchmaking Trading Stage*

In the matchmaking trading stage, the sellers' energy supply data and the buyers' demand data can be abtained from the state database. At the time of above order data being written to state database, all sellers' information data and all buyers' information data can be stored respectively in the state database according to the mark (i. e. the sign) and the delivery time. We can call them potential trading sets. And the value for sellers is the addresses of sellers. The value for buyers is the addresses of buyers. The keys stands for the type of sellers and buyers and the delivery time. That is, the naming rule of keys contains the information of user type and the delivery time.

Then, the potential trading sets related to sellers should be sorted internally according the selling price from low to high. The potential trading sets related to buyers should be sorted internally according the buying price from high to low. The above strategy means the lower selling price and the higher buying price have more advantages to complete energy trading match in advance.

After the completion of the sorting work, we can begin to carry out the matchmaking trading work. The detailed matchmaking trading proces is shown in Fig. 2.

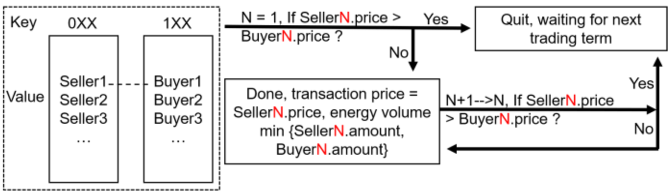

Figure 3. Matchmaking trading process

In the above picture, the Key "0XX" and "1XX" means the potential trading set related sellers and potential trading set related buyers has the same delivery time. The "XX" in "0XX" is the delivery time. For example, "008" means a seller could sell energy at 8:00 in the morning.

In this paper, we assumed that each energy transaction is executed between one seller and one buyer. The seller's selling price is sortd from low to high and the buyer's buying price is sorted from low to high in the potential trading sets. so, if the first seller's price is higher than the first buyer's price, all sellers' selling price is higher than all buyers' buying privce. Therefore, there is no available transaction in the energy trading term. The time span of an energy trading term could be determinted according to the actual situation.

In addition, after completion of a matchmaking trading energy, the seller's state and the buyer's state will be turned from 0 to 1. And the output of this stage contains the seller's address, the buyer's address, the delivery time, actual price and actual trading volume.

C. *The Transaction Execution Stage*

In the deliever time, the energy dispatch will be executed and the tokens will be transferred according to the result of the matchmaking trading stage. After the transaction execution, the key of the potential trading sets should be deleted from the state database such as CouthDB. After an energy trading term, if a seller's state or a buyer's state still is 0, the seller or the buyer will be join the next energy trading term automatically.

III. Formulation of Smart Contracts

In our approach, a smart contract is a piece of code that defines the expected logic. We use Go programming language, which is a statically typed, compiled programming language.

A. *Supply Order Contract of Energy Sellers*

The sellers should submit their supply orders on the smart contract. The submitted data will be written to the state database. The input of this contract is the delivery time, the sign, the seller address, the energy amount and the energy price. The function of this contract is to submit the supply orders to the state database. The basic elements of the supply order contract are shown in TABLE I.

TABLE I. Basic Elements of a Supply Order Contract

The Items of Contract	***Data Type***	***Meaning***
The seller address	String	It stands for account address of the seller, and will be used as the key of the struct "Seller".
The sign	Int	It is a label, and refers to the type of users. "0" is for seller.
The delivery time	Int	It refers to the energy supply time of a seller. "08" means 8:00 – 9:00.
Energy amount	Int	It refers to the volume of energy supply by the seller.
Energy price	Float32	It refers to the price of energy supply by the seller.
State	Int	It is a tag, and marks the seller whether the matchmaking trading has completed. "0" means the match has not been completed yet. "1" means the match has been completed.

In TABLE I, "String" refers to a sequence of characters, as a literal constant. "Int" refers to integer value. "Float32" refers to 32-bit floating-point numbers.

B. Demand Order Contract of Energy Buyers

The buyers should submit their demand orders on the smart contract. The submitted data will be written to the state database. The input of this contract is the delivery time, the sign, the buyer address, the energy amount and the energy price. The function of this contract is to submit the demand orders to the state database. The basic elements of the demand order contract are shown in TABLE II.

TABLE II. BASIC ELEMENTS OF A DEMAND ORDER CONTRACT

The Items of Contract	***Data Type***	***Meaning***
The buyer address	String	It stands for account address of the buyer, and will be used as the key of the struct "Buyer".
The sign	Int	It is a label, and refers to the type of users. "1" is for buyer.
The delivery time	Int	It refers to the energy demand time of a buyer.
Energy amount	Int	It refers to the volume of energy demand by the buyer.
Energy price	Int	It refers to the price of energy demand by the buyer.
State	Int	It is a tag, and marks the buyer whether the matchmaking trading has completed.

C. The Matchmaking Trading Contract

The matchmaking trading contract checks the delivery time and classifies buyers and sellers of the same delivery time. The contract then matches the sellers and buyers by the transaction mechanism presented in Section II. The basic elements of the contract are shown in TABLE III.

TABLE III. BASIC ELEMENTS OF A MATCHMAKING TRADING CONTRACT

The Parameters' Name	***Data Type***	***Meaning***
Seller address	String	It stands for account address of the seller.
Seller's energy quantity	Int	It refers to the volume of energy supply by the seller.
Seller's energy price	Float32	It refers to the price of energy supply by the seller.
Seller's delivery time	Int	It refers to the energy supply time of a seller.
Seller's state	Int	Here is "0".
Buyer address	String	It stands for account address of the buyer.
Buyer's energy quantity	Int	It refers to the volume of energy demand by the buyer.
Buyer's energy price	Float32	It refers to the price of energy demand by the buyer.
Buyer's delivery time	Int	It refers to the energy demand time of a buyer.
Buyer's state	Int	Here is "0".

D. The Settlement Contract

By means of the settlement contract, the credits can be automatically transferred according to the pre-agreed terms and deal terms during the delivery time of the transaction. The basic elements of the contract are shown in TABLE IV.

TABLE IV. BASIC ELEMENTS OF A SETTLEMENT CONTRACT

The Parameters' Name	***Data Type***	***Meaning***
Seller address	String	It stands for account address of the seller who has completed the match.
Buyer address	String	It stands for account address of the buyer who has completed the match.
Actual energy amount	Int	It refers to the actual energy transaction volume after successful match.
Actual price	Float32	It refers to the actual energy transaction price after successful match.
The delivery time	Int	It refers to the energy transaction time.

IV. CASE STUDY

To verify the effectiveness of the energy trading strategy proposed in this paper, the smart contracts for the P2P energy transaction are tested on HLF. There are four electricity buyers, in addition to four sellers, merely providing electricity in this test.

A. Deploying the Supply Order Contract of Electricity Sellers

The sellers need to make the supply orders which contains the delivery time, the sign, the seller account address, the energy amount, the selling price and the state. The sign stands for the user's type. 0 is for seller, 1 is for buyer. It is to distinguish the user's type when we deploy the matchmaking trading contract. The buyers' order information and the sellers' information can be sent to the key-value store state database, which is CouchDB. The four sellers' data is shown in TABLE V.

TABLE V. PARAMETERS OF SUPPLY ORDER OF FOUR SELLERS

The Parameters' Name	***Seller1***	***Seller2***	***Seller3***	***Seller4***
Address	0x67543 2edda323	0x6d5ec3 367cdf8	0x8d5e03 367cda6	0x3e5df54 24d2f7
Sign	0	0	0	0
Delivery_time	08	10	10	08
Price	1.6	1.7	1.8	1.9
Amount	80	90	100	70
State	0	0	0	0

The chaincode's input is the above parameters. When the chaincode is executed through deploying the Invoke function of HLF, the data will be stored in JavaScript Object Notation format and written to CouchDB.

B. Deploying the Demand Order Contract of Electricity Sellers

The buyers need to make the demand orders which contains the delivery time, the sign, the seller account address, the energy amount, the selling price and the state. The four buyers' data is shown in TABLE VI.

TABLE VI. PARAMETERS OF DEMAND ORDER OF FOUR BUYERS

The Parameters' Name	*Buyer1*	*Buyer2*	*Buyer3*	*Buyer4*
Address	0x7df45e cab7844	0x7df54e 9dcf7a7	0x6ed85f dcab456	0x67fd45e ca78de
Sign	1	1	1	1
Delivery_time	10	08	08	10
Price	1.8	1.9	1.6	1.8
Amount	80	70	100	80
State	0	0	0	0

The execution of this contract is similar as the process of deploying the supply order contract.

C. Deploying the Matchmaking Trading Contract

After the two executions of the two order contracts. We can query all the information data of the sellers and the buyers from the CouchDB. The contract then matches the sellers and buyers by the trading strategy presented in Section II. The sellers and the huyers participating in this matchmaking trading are respectively presented in TABLE VIand TABLE VI. The results of the sorted potential sets can be seen in Fig. 4.

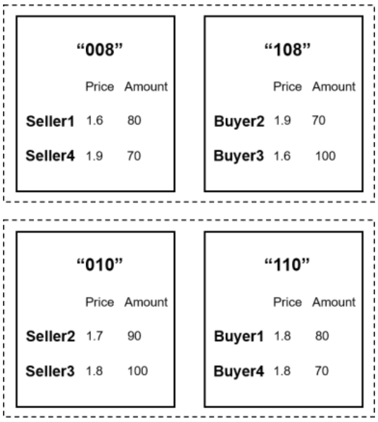

Figure 4. The results of the sorted potential sets

D. Deploying the Transaction Settlement Contract

After the execution of matchmaking trading process, the result of the match is shown in TABLE VII. Then by the delievery time, the transaction settlement contract can be executed according to the result of the matchmaking trading.

TABLE VII. THE RESULT OF THE MATCHMAKING TRADING

The Parameters' Name	*Match1*	*Match2*	*Match3*
Seller_address	0x675432edd a323	0x6d5ec3367cd f8	0x8d5e03367c da6
Seller_state	1	1	1
Buyer_address	0x7df54e9dcf 7a7	0x7df45ecab78 44	0x67fd45eca7 8de
Buyer_state	1	1	1
Delivery_time	08	10	10
Price	1.6	1.7	1.8
Amount	70	80	70

E. Trading Strategy Analysis

From the TABLE VII, the result of the energy transfer is available. It is shown in TABLE VIII. According to the matchmaking trading rules above proposed, the seller's selling price is sortd from low to high and the buyer's buying price is sorted from low to high before the matching, which means that a seller with a lower selling price has the priority over a seller with a higher selling price. If a seller is willing to sell his or her energy, a more lower selling price should be set in the supply order. On the contrary, a buyer with a higher buying price has the priority over a buyer with a lower buying price. If a buyer is willing to buy energy, a more higher buying price should be set in the demand order.

TABLE VIII. THE RESULT OF THE ENERGY TRANSFER

The Transaction Parties	*Seller's price*	*Buyer's price*	*Actual price*
Seller1→Buyer2	1.6	1.9	1.6
Seller2→Buyer1	1.7	1.8	1.7
Seller3→buyer4	1.8	1.8	1.8

In addition, a buyer with the more higher bid will instead execute the trading energy at a lower price. So, if most buyers set higher buying price, the possibility of completing trading match is more bigger by reason of the transaction match rules. The rules is that the buying price is higher than the selling price. At the same time, the buyers with higher buying price will run a big risk in completing the energy trading in a more higher transaction price if most sellers set a higher selling price and the selling prices are lower than the most buying price.

From the above analysis, the sellers and the buyers are mutual restraint from the perspective of interest. Therefore, the energy trading strategy proposed is reasonable and feasible in the realistic scenario.

V. CONCLUSION

This paper discussed the application of blockchain technology in the energy trading and put forward a decentralized trading strategy, including the realization process of the smart contracts.

The transaction process put forward in this paper is divided into three stages: the order submission stage, the matchmaking trading stage and the transaction execution stage. The authors designed and deployed the trading smart contracts on Hyperledger Fabric (HLF), in addition to verifying the trading process. In consideration of the simplicity of the trading strategy, a seller can only trade with a buyer after matchmaking. The proposed strategy can fit the demand of the distributed, small-scale and low-cost transaction of the energy resources in MGs.

Further studies will focus on two major parts: firstly, setting up a platform to put the P2P trading strategy into practice, and evaluating its effectiveness and practicability. Secondly, designing the one-to-many and many-to-many trading strategy in the integrated energy.

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