A high-performance local energy trading cyber-physical system based on blockchain technology

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Abstract. The traditional electricity markets are facing challenges in integrating the distributed generation extensively. However, the local energy markets have the potential to support the local integration of DG and facilitate the local balance of energy supply and demand. The operation and management of local energy markets require support from the efficient and reliable information technology. Blockchain technology has the potential to be used in local energy trading, but it is difficult to support frequent trades among the rising number of market participants, due to the basic design principle of the technology. Therefore, we present the off-chain energy trading method and an asynchronous transaction recording mechanism to ensure the efficiency of energy trading procedures. To support off-chain energy trading, we design a local energy trading cyber-physical system. The overview of the local energy market and the framework of the blockchain-based local energy trading system are illustrated respectively.

1. Introduction

Distributed generation (DG) is defined as a small-scale electricity generation [1], which is performed by a variety of distributed energy resources. The Chinese government proposed to give priority to the development of distributed photovoltaic (PV) and will develop user-side distributed energy markets to encourage the development of distributed energy, smart grids and microgrids in the 13th Five-Year Plan [2]. In 2017, the installed capacity of distributed PV power generation in China increased by 19.44 GW [3]. However, the traditional electricity markets are facing challenges in integrating the DG extensively [4].

Local energy market, which integrates the DG, microgrid and smart grid into one electricity market at distribution side [4], has the potential to support the local integration of DG and facilitate the local balance of energy supply and demand [5]. In a local energy market, plenty of small-scale prosumers (the entities not only consume energy, but also generate energy and share the surplus energy with the utility grid or other energy consumers) [6] with volatile renewable generation and individual consumers will be approved to join in the energy trading activities. Moreover, the well-designed incentive mechanisms will guide the market participants to invest in local generation and storage facilities, which will facilitate the local balance of generation and consumption [7].

Cyber-Physical Systems (CPS) are integrations of computation with physical processes [8]. In the CPS, physical and software components are deeply intertwined, which operate on different spatial and
temporal scales, exhibit multiple and distinct behavioral modalities and interact with each other [9]. The operation and management of local energy markets require support from the efficient CPS. To support the frequent trades among the rising number of market participants, new information technologies should be introduced into the energy trading cyber-physical systems. In the recent years, several research projects studied the potential application of the blockchain technology in energy trading, and some of them designed different frameworks of energy trading systems in different scenarios.

Blockchain was invented by Satoshi Nakamoto in 2008 for using in the public transaction ledger of cryptocurrency named Bitcoin [10]. It is a typical distributed computing system with high Byzantine fault tolerance [11]. The mechanisms of decentralized consensus guarantee the consistency of the data stored in each node. Once recorded, data on the blockchain cannot be modified. The technology of blockchain is potentially suitable for recording the transaction data in the local energy markets.

Chenghua Zhang et al. [12] design an online trading platform ‘Elecbay’ used for the Peer-to-Peer (P2P) energy trading in a microgrid. Their work demonstrates the possibilities and potential benefits of integrating P2P energy trading in local power networks. Jiwen Kang et al. [13] propose a localized P2P electricity trading system with consortium blockchain method to support the operations of localized P2P electricity trading among plug-in hybrid electric vehicles. Their work indicates that a double auction mechanism, which executes energy bidding and transaction, can achieve social welfare maximization. Zhetao Li et al. [14] present a consortium blockchain for secure energy trading in industrial Internet of things, they also propose a complex credit-based payment scheme to accelerate the trading processes.

Esther Mengelkamp et al. [15] describe a framework containing seven components for building efficient microgrid energy markets. They evaluate the Brooklyn microgrid project, which is a microgrid energy market based on a private blockchain, and they confirm that private blockchains are suitable information systems which can facilitate localized energy markets.

The on-chain energy trading means market participants buy or sell energy directly with each other without intermediation, and each transaction’s information requires to be recorded synchronously on the blockchain. Considering the frequent trades among a great number of market participants will generate a massive amount of transaction information, the energy trading system should be efficient enough to deal with the energy trading processes. Because the basic design principle of blockchain technology is sacrificing availability to ensure consistency and partition tolerance, it is not suitable to use blockchains to store each transaction’s information directly.

The contribution of this paper can be summarized as follows. This paper presents the off-chain energy trading method and an asynchronous transaction recording mechanism to overcome the main drawback of blockchain technique discussed above and ensure the efficiency of energy trading procedures. To support the frequent off-chain energy trading among the rising number of market participants, this paper designs a local energy trading cyber-physical system. The overview of the local energy market and the framework of the blockchain-based local energy trading system are illustrated respectively in this paper.

The structure of this paper is summarized as follows. In Section 2, the overview of local energy market is presented. Section 3 introduces the framework of the local energy trading system. Section 4 concludes the whole paper.

2. Overview of the local energy market
A local energy market, which is based on off-chain energy trading, is presented in this section. The off-chain energy trading method introduces the exchange centres to guarantee the efficiency of energy trading, and the details of the method will be illustrated in Section 3. The typical energy trading scenarios, the common entities and the interactions among the entities in local energy markets will be discussed to illustrate the framework of the local energy market.
2.1. Typical energy trading scenarios in the local energy markets

Figure 1 shows three typical local energy trading scenarios in the microgrids and describes how electricity, data and capital flow in the microgrid.

1) The energy prosumers with PV panels can sell surplus energy to nearby energy consumers [16].
2) The electric vehicles can sell surplus energy in their batteries to other electric vehicles through charging stations [13].
3) The distributed photovoltaic power stations can also supply energy for neighbouring energy consumers [16].

All of these participants can trade electric energy by the off-chain energy trading method, which will be further illustrated in Section 3.

2.2. Common entities in the local energy markets

The local energy market consists of four common entities as follows:

1) Local energy seller: The market participants (e.g., distributed photovoltaic power station, cogeneration units and electric vehicles) with surplus electric energy can sell energy to the local buyers or electricity retailers.
2) Local energy buyer: The market participants with energy demand can buy electric energy from the local sellers or electricity retailers.
3) Microgrid power exchange centre: There is a microgrid power exchange centre in each microgrid. The entity’s responsibilities contain collecting and matching trading requests from buyers and sellers within the microgrid and publishing clear prices regularly. Besides, the microgrid power exchange centre is also responsible for the examination and approval of market access and evaluating if there is going to be a network constraint violation.
4) Regional power exchange centre: There will be several microgrids in a region, and the regional power exchange centre has the responsibility to evaluate if there is going to be a network constraint violation in the region. It should be particularly noted that the regional exchange center is not responsible for recording the transactions on the blockchain. Therefore, there is still no absolute central organization in the region, and the microgrid power exchange centres can be considered as peers.

All of the buyers and sellers are assumed to be self-interested and rational in the market, but the exchange centres should be reliable, fair and impartial.

Before the introduction of the relatively complex interactions among the entities, the following assumptions were made:

1) Most of the buyers and sellers (except for the traditional energy suppliers) are self-interested and rational in the market [17]. They always tend to maximize their revenue and minimize their energy costs.
2) Traditional energy suppliers, such as the electricity retailers, are passive to quote, they always choose to buy energy from the local sellers with constant and the lowest unit prices and sell energy to the local buyers with fixed and the highest unit prices [12].

3) The electricity retailers can always supply sufficient electric energy or consume surplus energy for the microgrids, when the demand and supply are not balanced in the local market.

4) The number of market participants is stable in the short term.

2.3. Interactions among the entities

Figure 2 describes the flow of power, data and capital among the participants in the local energy market. In the local energy market, the interactions among the entities, who choose to trade by the off-chain method, can be simplified as following items.

1) The participants should submit application forms to the local microgrid power exchange centre to join the local energy market. And the exchange centre will reply them with the audit result.

2) Energy sellers and buyers should submit trading request messages, which contain trading time period, quantity and quoted price, to the local microgrid power exchange centre.

3) If the demand and supply are not balanced within the microgrid, the local microgrid power exchange centre will communicate with the regional power exchange centre to confirm the electricity retailers will fill the gap between demand and supply within the microgrid.

4) If the local microgrid power exchange centre finishes transactions matching and security correction, the result of the clearing will be published to all of the participants.

5) The smart meters record the actual energy consumption or generation and send these data to the local microgrid power exchange centre. If there exists disparity between the arranged amount and actual amount, the gap will be filled by the electricity retailers, and the electricity fees will be recalculated by the exchange centre.

6) After the settlement period, the electricity fees will be automatically transferred from the buyers' transaction accounts to the sellers' transaction accounts. The transaction information will be recorded on the blockchain through an asynchronous transaction recording mechanism.

Although the procedures of off-chain energy trading seem quite complex, the efficiency of transaction confirming and recording can be guaranteed, because of the integration of the asynchronous transaction recording mechanism and the high-speed communication networks among the power exchange centres. Besides, it will be efficient to find the right one to trade with in the power exchange centres. More details of the off-chain energy trading method will be introduced in Section 3.

3. Framework of local energy trading system

The framework of local energy trading system, which supports off-chain energy trading, is shown in Figure 3. There will be several microgrids and a regional power exchange centre in a region (e.g., a city or a county). The main components of the trading system, the off-chain energy trading method and the asynchronous transaction recording mechanism will be illustrated in this section.

3.1. Main components of the energy trading system

There is a microgrid power exchange centre in each microgrid, the main devices in a microgrid power exchange centre contain the transaction server, meter reading server, account database and transaction database. And their functions are illustrated in Table 1. This paper does not mention some of the necessary network facilities to simplify the narration.

The market participants are equipped with the smart meters, which are responsible for measuring and uploading the accurate information of power generation and consumption almost in real time. Each participant has a transaction account and a blockchain wallet. The participants need to transfer sufficient funds from the blockchain wallets to the transaction accounts in advance. After the two parties reach a transaction, which has got the exchange centre’s approval, the exchange centre will firstly freeze the electricity fees in the buyer's transaction account. When a transaction finished, the electricity fees will be recalculated, according to the quoted price, actual power generation and actual
power consumption. After the settlement process, the electricity fees will be automatically transferred from the buyers' transaction accounts to the sellers' transaction accounts. The participants can also transfer their funds from the transaction accounts to their blockchain wallets.

![Figure 3. Framework of local energy trading system.](image)

**Table 1. Main devices in the local energy trading system**

| Devices            | Functions                                                                 |
|--------------------|---------------------------------------------------------------------------|
| Transaction server | (1) Collecting trading requests from buyers and sellers                    |
|                    | (2) Matching the trading requests                                          |
|                    | (3) Publishing the clear price regularly                                   |
| Meter reading server| Collecting data from the smart meters in the microgrid                     |
| Account database   | Recording the information of accounts                                      |
| Transaction database| Recording the information of transactions                                 |
| Smart meter        | Measuring the information of power generation or consumption.              |

3.2. **Off-chain energy trading method**

In the local energy market, the off-chain energy trading activities are open, and the microgrid power exchange centres are independent and reliable, which means the exchange centres can be responsible for checking the trading application and recording the authentic transaction information on blockchain.

The off-chain energy trading method plays a vital role in improving the performance of the energy trading system, and the procedures of off-chain energy trading will be further introduced in the following paragraphs of this section.

To join in the local energy trading, the energy sellers and buyers should register in the local microgrid power exchange centre and submit application forms to the exchange centre. The exchange centre will check the facticity of the application forms and choose to accept or reject the accession of the applicants. If an applicant is accepted, its basic information (e.g., the power generation capacity, the storage capacity, contact method and the trading account balance) will be recorded in the account database in the local exchange centre.

Figure 4 describes that an off-chain energy transaction will go through four major stages. The time from the start of bidding to the end of the matching is limited to a period of time, whose length is no more than the length of energy delivery stage. Thus, the energy transmission can be continuous, and the bidding procedure and matching procedure require to be efficient enough.

The local market participants need to buy or sell electricity several hours in advance, as shown in Figure 4. During a fixed-length bidding stage, participants need to submit the trading request messages, which contain the type of transaction (buy or sell), quoted prices and quantities to the local microgrid power exchange centre. The operation of quotation needs to be repeated many times in one day, so it is
necessary to develop trading programs and design suitable trading strategies to complete the frequent quotation operations through automatic means. In the meantime, most of the buyers and sellers are supposed to be self-interested and rational in the market, so they always tend to find the ideal quotation strategies to maximize their revenue and minimize their costs.

The matching stage is the second stage, during which the transaction servers in the local microgrid power exchange centre match energy trading requests according to the principle of maximizing trade volume. And then, the exchange centre will evaluate if there is going to be a network constraint violation and choose to accept or reject the matched transactions according to the results of security correction. If the demand and supply are not balanced within the microgrid, the local microgrid power exchange centre will communicate with the regional power exchange centre to confirm the electricity retailers will fill the gap between demand and supply within the microgrid during the certain stage. At the end of the matching stage, the local microgrid power exchange centre will publish the result of matching to all of the local energy market participants and freeze corresponding money in the buyers' transaction accounts for paying electricity fees.

In the energy delivery stage, the smart meters record the actual data of power consumption or generation and send these data to the local microgrid power exchange centre. If there exists disparity between the arranged amount and actual amount, the gap will be filled by the electricity retailer, and the electricity fees will be recalculated by the exchange centre. During the settlement stage, the electricity fees will be audited and transferred from the buyers' transaction accounts to the sellers' transaction accounts.

![Figure 4. The procedures of an off-chain energy transaction.](image)

### 3.3. Asynchronous transaction recording mechanism

The off-chain energy trading method empowers the power exchange centres to check the trading application and record the authentic transaction information on blockchain. But the suited transaction recording mechanism still need to be designed. The typical blockchains are often designed to pack each transaction generated in a period of time into a new block and then connect the new block to the end of the blockchain. But the main drawback of this approach is that it is susceptible to great changes in the number of transactions. When the actual number of transactions suddenly increases, it is quite likely to occur severe congestion. The congestion may disturb the trading processes and the normal power supply, which is unacceptable in local energy market.

This paper proposed an asynchronous transaction recording mechanism to restrict the frequent reading and writing of transaction data recorded on the blockchain. Specifically speaking, the mechanism allows local microgrid power exchange centre to record each user’s transactions within a day (or a week) in its databases and then aggregate these transactions into a single transaction between the user and the exchange centre. The aggregated transactions will be packed into blocks, and these newly created blocks will be connected to the blockchain.

In fact, the main idea of the asynchronous transaction recording method is to decouple the number of transactions, which require to be recorded on the blockchain, from the trading frequency. In this condition, the number of aggregated transactions generated in a period of time is almost fixed regardless of the actual trading frequency, because the number of market participants is supposed to be stable in the short term. Moreover, the power exchange centre can schedule the transaction recording tasks reasonably in advance to avoid the emergence of congestion.
3.4. Deviation handling mechanism
If there exists deviation between the arranged amount in the transaction information and actual amount recorded by smart meters, the gap will be filled by the electricity retailers to ensure the balance of supply and demand. Because the electricity retailers are assumed to buy energy from the local sellers with the lowest unit prices and sell energy to the local buyers with the highest unit prices, there will always be a price difference between the arranged price in the transaction information and the quotation of electricity retailers, if the deviation part of energy needs to be get from electricity retailers. The price difference will be paid by the defaulting party, who is mainly responsible for the deviation. It represents the penalty for the deviation. In addition, if a market participant often causes evident deviations, it will be banned from the market temporarily or permanently.

The setting of deviation punishment mechanism aims at guiding users to submit reasonable trading requests and maintaining the market order. On the other hand, the long-term existence of the price difference mentioned above can stimulate the construction of local power generation and storage facilities, which is conducive to the balance of supply and demand, as well as a reduction in the consumers' electricity expense.

3.5. The performance improvement of blockchain-based energy trading system
The efficiency of transaction handling is limited by block size, average block creation interval and transaction confirmation delays in Bitcoin blockchain, which can only handle seven transactions per second [18]. Therefore, this paper presents the off-chain energy trading method which makes full use of the reliable exchange centres’ endorsements to guarantee the authenticity of the transaction information recorded by the exchange centres. In this condition, the long confirmation delays are no longer needed for avoiding double-spending, which means the transaction confirmation delays can be reduced to few minutes, and the trading processes can be accelerated significantly.

Moreover, thanks to the support from the high-speed communication networks among the power exchange centres, the size of blocks and the average block creation interval can be adjusted within a certain range according to the changes in the number of market participants. This adjustment mechanism can ensure the efficiency of the transaction handling.

The asynchronous transaction recording mechanism can improve the trading system’s ability of supporting high-frequency energy trading, and avoid the emergence of serious congestion. The integration of the off-chain energy trading method and the efficient transaction recording method can guarantee the performance of the blockchain-based energy trading system.

4. Conclusion
In this paper, we illustrate the overview of the local energy market, which has the potential to support local integration of DG and facilitate the local balance of energy supply and demand. To support frequent trades among the rising number of market participants, this paper designs a blockchain-based local energy trading cyber-physical system. This paper also presents the off-chain energy trading method and an asynchronous transaction recording mechanism to ensure the efficiency of energy trading procedures. The mechanisms in the local energy trading system can stimulate the construction of local power generation and storage facilities, which is conducive to the balance of supply and demand, as well as a reduction in the consumers' electricity expense.

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