A Blockchain based Distributed Controllable Electricity Transaction Matching System

Songpu Ai
Energy Internet Lab
MingByte Technology (Qingdao) Co., Ltd.
Qingdao, China
aisp@mingbyte.com

Diankai Hu
Energy Internet Lab
MingByte Technology (Qingdao) Co., Ltd.
Qingdao, China
hudk@mingbyte.com

Jian Guo
Research Institute of Information Technology
Tsinghua University
Beijing, China
guoj2019@tsinghua.edu.cn

Yunpeng Jiang
Energy Internet Lab
MingByte Technology (Qingdao) Co., Ltd.
Qingdao, China
jiangyp@mingbyte.com

Chunming Rong
Department of Electrical Engineering and Computer Science
University of Stavanger
Stavanger, Norway
chunming.rong@uis.no

Junwei Cao
Beijing National Research Center for Information Science and Technology
Tsinghua University
Beijing, China
jcao@tsinghua.edu.cn

***Abstract*—A large number of individual power prosumers are emerging and participating in the regional energy internet (REI) with the rapid development of the power generation technology of distributed renewable energy. The increasing scale of the REI may bring challenges to the traditional centralized electricity trading and match platform in the REI. However, at the present stage, distributed electricity transaction platform based on blockchain mostly adopts traditional mechanisms such as double auctions, which may exist problems in practical utilization such as the match of clean energy is relatively difficult, the waste of electricity transmission is hard to be indicated, and the electricity seller cannot choose the electricity purchaser, etc. In this paper, a blockchain based distributed controllable electricity transaction matching system is designed and implemented in order to propose a feasible system to overcome the existing challenges. The automatic match of a single transaction on the blockchain is implemented based on smart contract technology in the system, which avoids the interference of the number of transactions and the matching cycle on the matching speed of single transaction in the matching process. Experimental results indicated that compared with traditional solutions, the supply proportion of clean energy in the entire REI increased from 4.69% to 78.15% by adopting the proposed system, and the electricity transmission loss in the entire REI is reduced by 1.08%.**

Keywords—blockchain, distributed electricity transaction match, regional energy internet

I. Introduction

With the development of the power generation technology of distributed renewable energy (PGTDRE) and the continuous progress of internet technology, the concept of regional energy internet (REI) has been proposed [1-4]. REI is one of the important means to deal with the problems of urbanization in many countries [5-6]. With the promotion of PGTDRE, numerous of prosumers access the REI to participate in electricity transactions. Electricity trading has gradually evolved from traditional single energy centralized trading to diversified comprehensive energy trading [7]. The process of transaction match becomes rather complicated, which makes it difficult for conventional centralized management to be competent for the new scenario.

In the traditional electricity market, most of the entities adopt a centralized matching model for electricity transactions, consumers generally trade indirectly with renewable energy suppliers through third-party centralized institutions [8-10]. Although centralized trading solves the problem of trust among consumers, with the increasing number and types of electricity transactions in the REI, the operating cost of the centralized matching model is increasing [11-12]. Furthermore, the centralized storage of transaction data exists certain information security risks [13]. At the same time, centralized matching is generally could not be triggered until the transaction reaches a certain number or the time reaches the cycle time. Based on the above reasons, the traditional centralized matching may not be able to meet the scenario of diversified comprehensive energy trading in the REI.

As the underlying technology of Bitcoin [14], blockchain has the characteristics of trustworthy, tamper-proof [15-16], decentralization [17], etc. It has become research trend to apply it to diversified comprehensive energy trading [18]. At present, distributed energy transaction models based on blockchain at home and abroad mainly include P2P transactions between individuals and centralized clearing with intermediaries [19]. In the first model, both parties to the transactions need to agree on the price in advance, the blockchain platform only provides the function of recording transactions, and this model lacks an electricity matching mechanism for the users' needs. In the second model, electricity transactions need to be centrally matched by middlemen, the blockchain platform only provides the function of completing settlement based on transaction records.

In response to the deficiencies of existing distributed energy transaction models, a distributed controllable electricity transaction matching system based on blockchain is designed and implemented in this paper. The suitability of multiple factors such as electricity price, transaction volume, transmission distance, and energy type were calculated and compared in the proposed system. This system is conducive to promoting small-scale clean energy producers to actively participate in energy transactions in the REI and reducing the loss of energy in the transmission process. For the challenge that the electricity seller cannot select the electricity purchaser, the function of confirming matching records by private key signature was designed based on asymmetric cryptographic, so that the matching results can be controlled by both parties to the electricity transaction, the electricity seller can choose the electricity purchaser by themselves. The automatic match of single transaction based on multiple factors was realized by smart contract technology, which avoids the influences of

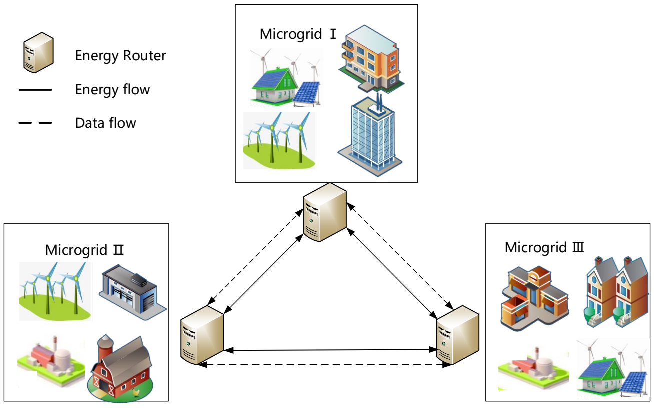

Fig. 1. System application scene graph.

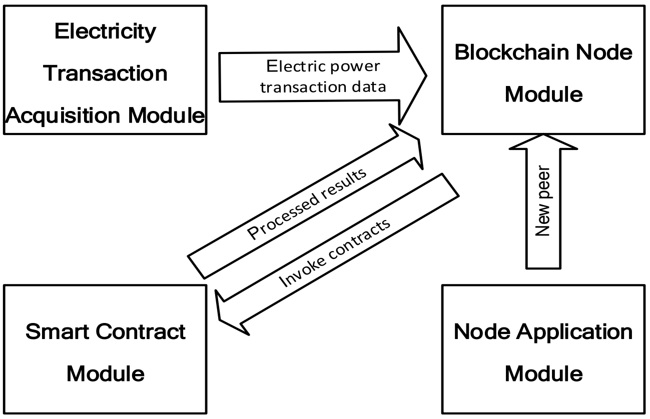

Fig. 2. Distributed controllable electricity transaction matching system based on blockchain

the number of transactions and the matching cycle on the matching speed of single transaction in the matching process.

The rest of this paper is organized as follows. Related researches of this work are introduced in Section II. In Section III, the application scenario, system framework and specific implementation of distributed controllable electricity match system based on blockchain are described. Based on the scenario of REI, the proposed system was experimentally tested and the test results were analyzed in Section IV. Finally, this paper is summarized in Section V.

II. RELATED WORKS

Li et al. analyzed the existing distributed energy transaction methods and their disadvantages, studied the applicability of blockchain technology to distributed energy P2P transactions, and proposed a distributed energy trading scheme based on blockchain [20]. However, it was not an available system. Mengelkamp et al. proposed a decentralized market trading platform based on blockchain [21], which allows prosumers to conduct double trade to consume renewable energy in the market in real-time. However, the platform did not design a corresponding matching mechanism for the price gap between renewable energy and fossil energy. LO3 Energy and Siemens jointly developed a blockchain-based microgrid trading platform [13] and designed a matching mechanism of double auctions (DA). However, the platform did not have a bidding strategy model and settlement mechanism based on blockchain. Wang et al. proposed an electricity transaction model of microgrid and quotation strategy based on blockchain and continuous DA mechanism in order to realize the direct transaction between the distributed electricity provider of the microgrid and users of electricity [22]. However, this model mainly focused on the timely adjustment of quotations based on market changes and digital electricity transaction vouchers are transmitted to users for electricity settlement based on blockchain. Zhao et al. proposed a blockchain-based comprehensive energy trading mechanism based on the principle of electricity transaction match [23], which divided the matching process into two stages: centralized matching and continuous DA matching. The former centrally match through third-party institutions which does not apply to multi-node transactions, and the latter mainly ranked and matched based on the price. Morstyn et al. proposed a bilateral contract network in P2P energy trading [24], which implemented P2P energy transactions among electricity generators, suppliers, and producers by intermediate agents. But the matching process is still completed by the middleman, and distributed electricity match has not been achieved. Luo et al. proposed an agent alliance mechanism [25], producers can negotiate electricity transactions through the agent alliance. However, the specific electricity transaction matching mechanism has not been proposed, it is only based on the blockchain for electricity transaction settlement.

III. MULTI-FACTOR ELECTRICITY TRANSACTION MATCHING MECHANISM

A. Application scenario

The proposed system applies to the scenario of the REI. The specific scenario is shown in Fig. 1. The REI is composed of several microgrids. Each microgrid contains multiple small-scale electricity producers, multiple electricity purchasers, and at least one energy router containing a blockchain node. Energy routers are mainly used for electricity transmission. Blockchain nodes are mainly used to submit electricity transaction data to the blockchain network.

B. System framework

The function of electricity match in the proposed system is realized by the blockchain-based multi-factor electricity transaction matching mechanism. The mechanism is proposed in another paper of our research related to transaction matching research which is under peer review [26]. In this paper, the blockchain based system which could feasible for the distributed controllable electricity transaction match is discussed. This work is also a continuation of our former paper [27] about electricity transaction asynchronous settlement system.

In the proposed system, fully automatic execution of transaction match, record on-chain and fund settlement in the blockchain are implemented. Further, the function of private key sign matching records is implemented in this system, so that users can control whether to complete electricity transaction match. The overall architecture of the system is shown in Fig. 2, which mainly includes node application module, electricity transaction acquisition module, blockchain nodes module and smart contract module.

Node application module: This module is mainly for new users to complete the node registration application. After the application is successful, the new user's blockchain node is added to the blockchain nodes module. To ensure the consensus efficiency of the blockchain system, blockchain nodes and users can adopt a one-to-many approach.

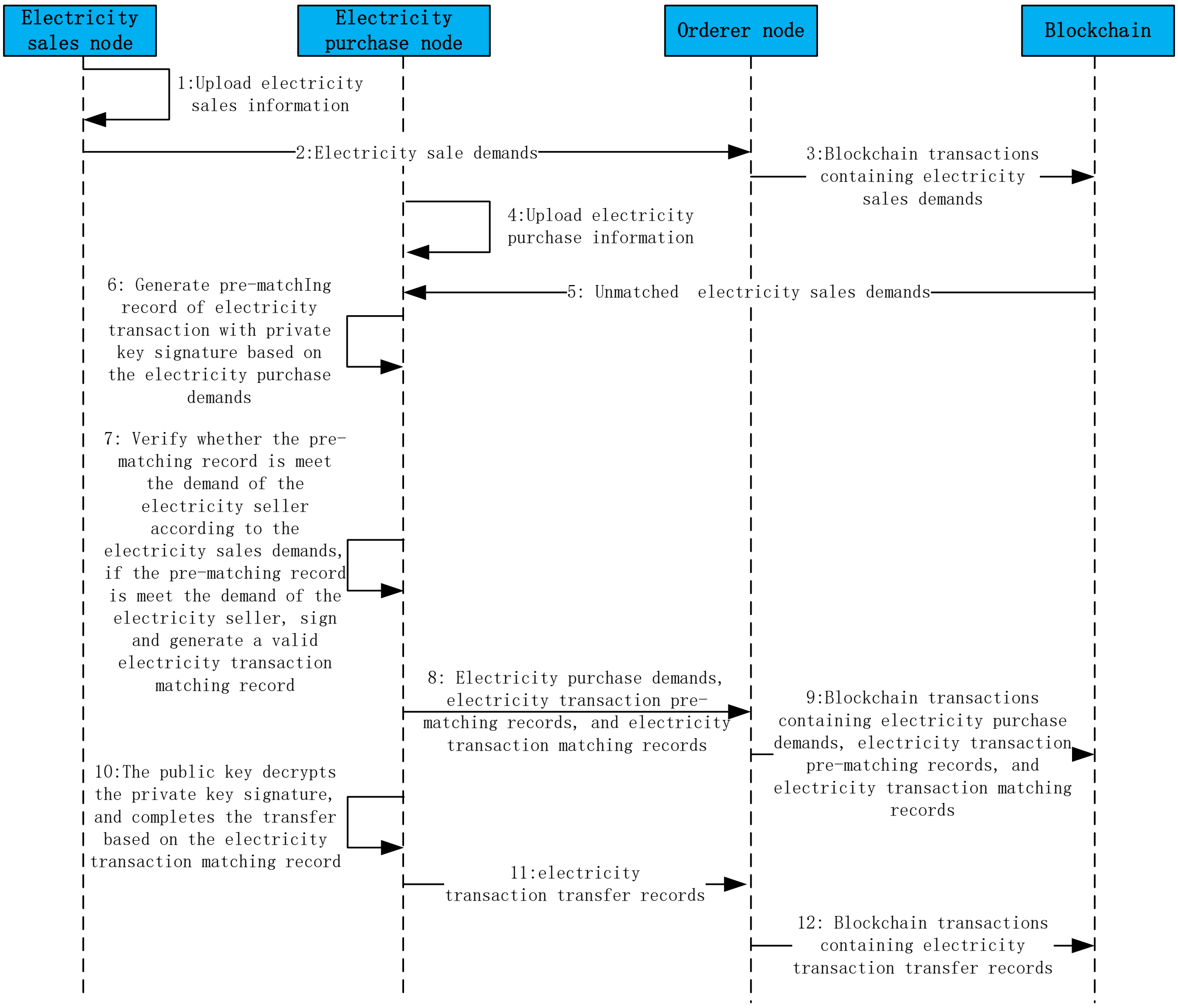

Fig. 3. Data sequence diagram of this system

Electricity transaction acquisition module: This module is mainly for users to submit electricity sale information or electricity purchase information to blockchain nodes according to their preferences, which in turn triggers smart contracts to automatically generate corresponding blockchain transactions based on the submitted information and store them on the chain. Finally, the electricity transaction match is automatically completed through smart contracts to provide users with more suitable electricity match.

Blockchain node module: The consensus of blockchain transactions in the blockchain network is completed through blockchain nodes in this module. Blockchain nodes mainly include user nodes and sorting nodes. User nodes are mainly divided into electricity sale nodes and electricity purchase nodes for users to complete electricity transactions. Sorting nodes are mainly used to sort blockchain transactions and reach a consensus. The function of off-chain data upload and the function of on-chain data query are realized by blockchain nodes, which are windows for users to interact with the blockchain network.

Smart contract module: This module is mainly used for blockchain nodes to call smart contracts with corresponding functions. The contracts of this system mainly include electricity sale demands generation contract (ESDGC) and transaction match settlement contract (TMSC). ESDGC is mainly used for electricity sale nodes to call, generates electricity sale demands based on electricity sale information and stores them on the chain. TMSC is mainly used for electricity purchase nodes to call, generates electricity purchase demands based on electricity purchase information and stores them on the chain. After that, the electricity match according to the user's preferences in the electricity purchase demands and the money transfer according to the matching record are completed by TMSC.

C. *Mechanism implementation*

Based on the Hyperledger Fabric project [28], a distributed controllable electricity transaction matching system based on blockchain is developed and implemented in this paper. Among them, the electricity sale nodes and the electricity purchase nodes are Peer nodes in the Hyperledger Fabric project, which are convenient for users to complete electricity transactions; the sorting nodes are the Orderer nodes, which are mainly used to collect blockchain transactions in the Peer organizations and reach Raft consensus. And the fully automatic execution of transaction match, record on-chain and fund settlement in the blockchain are implemented in this system. Further, the function of private key sign matching records is implemented in this system, so that users can control whether to complete electricity transaction match. The data flow of specific implementation is shown in Fig. 3, which mainly includes the following 12 steps.

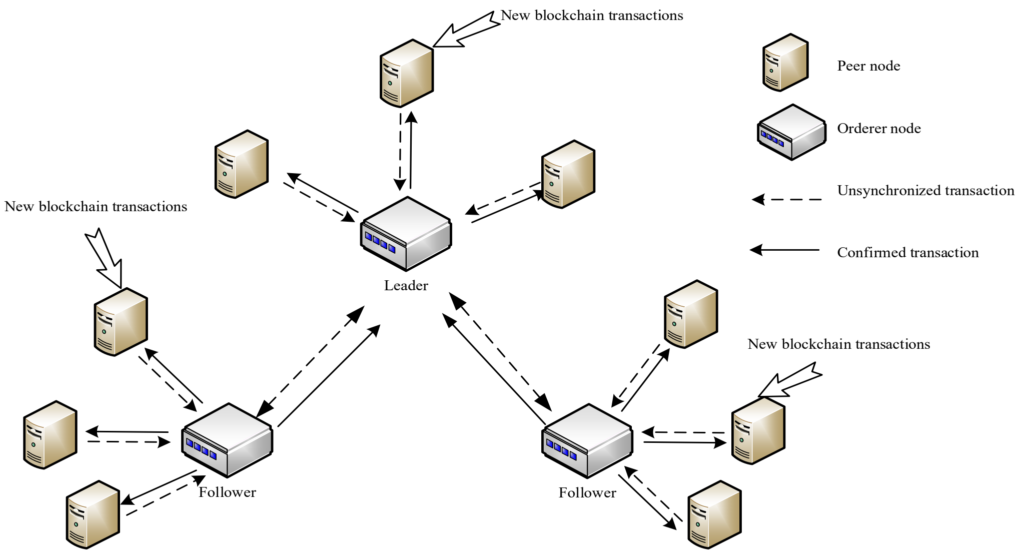

Fig. 4. Raft consensus process.

Step 1: The electricity sellers upload electricity sale information to the electricity sale node. The electricity sale information contains the electricity seller's demands for matching records of electricity transactions.

Step 2: The electricity sale node executes the ESDGC to generate electricity sale demands based on the electricity sale information and transmits them to the Orderer node.

Electricity sale demands mainly include attributes such as electricity price, environmental protection index, available electricity, energy types, and electricity supply location. Among them, the environmental protection index refers to the supply proportion of clean energy.

Step 3: The Orderer node collects transactions in the blockchain network and reaches Raft consensus. The blockchain transactions containing electricity sale demands are stored on the chain.

Step 4: The electricity purchasers upload electricity purchase information to the electricity purchase node. The electricity purchase information contains the electricity purchaser's demand for matching records of electricity transactions.

Step 5: The electricity purchase node executes the TMSC to generate electricity purchase demands based on the electricity purchase information. The electricity purchase node obtains effective electricity sale demands through the blockchain.

Electricity purchase demands mainly include the expectations of electricity purchasers on attributes such as environmental protection index, electricity purchase price, available electricity, energy types, transmission loss, and other attributes.

Step 6: The TMSC matches the electricity purchase demands according to the multi-factor electricity transaction matching mechanism, and generates a pre-matching record of electricity transaction with a private key signature.

The pre-matching record of electricity transactions mainly includes attributes such as private key signature of the electricity purchaser, trading price, transaction volume, and transmission loss.

Step 7: The TMSC verifies whether the pre-matching record of electricity transaction meets the demand of the electricity seller according to the electricity sale demands. If the pre-matching record meets the demand of the electricity seller, it will automatically sign and generate a valid electricity transaction matching record.

The matching record of electricity transaction is added with the private key signature of the electricity seller on the basis of the pre-matching record of electricity transaction.

Step 8: The electricity purchase node uploads electricity purchase demands, pre-matching records of electricity transaction, and matching records of electricity transaction to the Orderer node.

Step 9: The Orderer node collects transactions in the blockchain network and reaches Raft consensus. The transactions including electricity purchase demands, pre-matching records of electricity transaction, and matching records of electricity transaction are stored on the chain.

Step 10: The electricity purchase node verifies the private key signature of the electricity seller in the matching record of electricity transaction by public key decryption technology. If the verification is successful, a corresponding electricity transaction transfer record is generated.

Step 11: The electricity purchase node uploads the electricity transaction transfer record to the Orderer node.

Step 12: The Orderer node collects transactions in the blockchain network and reaches Raft consensus. The blockchain transactions containing the electricity transaction transfer records are stored on the chain.

The Raft consensus mechanism is adopted in this system, and the specific process is shown in Fig. 4. After the ordinary users upload electricity sale information or purchase information, the corresponding Peer nodes encapsulate information into blockchain transactions and send them to Orderer nodes. Orderer nodes send blockchain transactions to the Orderer node as the Leader. The Leader node sends the

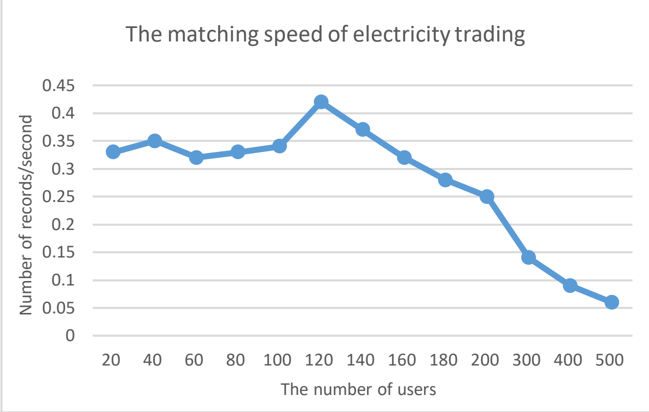

Fig. 5. The matching speed of electricity trading

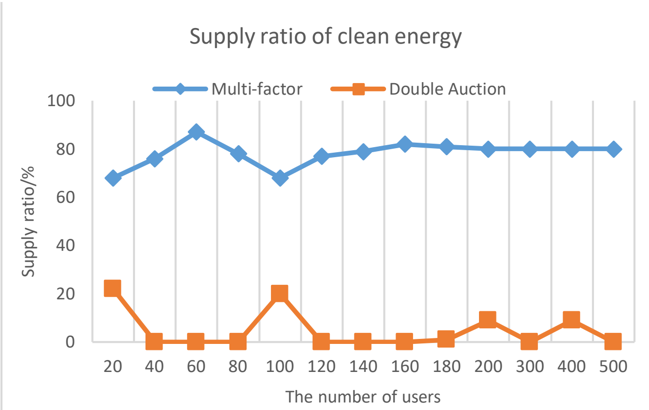

Fig. 6. Supply ratio of clean energy

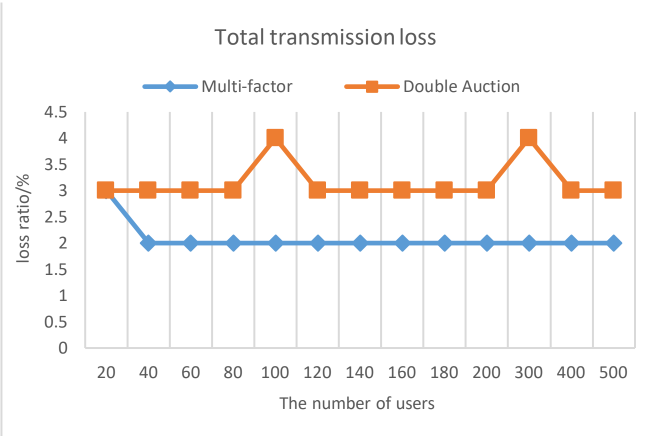

Fig. 7. Total transmission loss of REI

blockchain transactions to all Orderer nodes who are Follower identities. Follower nodes confirm the blockchain transactions and return the confirmation information to the Leader node. After the Leader node receives the confirmation information of most Follower nodes, it sends the confirmation information of the blockchain transactions to all Follower nodes. All Orderer nodes complete the on-chain storage of blockchain transactions. And all Peer nodes complete the synchronous on-chain storage of new blocks through Orderer nodes.

IV. Implementation and Performance Evaluation

A. Experimental test environment

The proposed system is implemented based on Hyperledger Fabric v1.4.4. The experimental equipment is five virtual machines with 2 core 2GB. The operating system on the virtual machine is Ubuntu 18.04.4 LTS (GNU/Linux 4.15.0-96-generic x86_64). Each virtual machine is deployed with one Peer node, and each Peer is connected to multiple users in the microgrid.

The proposed mechanism is based on the application scenarios of REI. In this experiment, it is set that the REI contains 5 microgrids, and each microgrid corresponds to a blockchain node. Users concurrently submit electricity transaction information through blockchain nodes. In this system, the block-timeout is set to 2 seconds, and the maximum number of block transactions is set to 50. Refer to the paper [26] for the setting of relevant experimental parameters such as electricity price.

B. Analysis of results

The matching speed of electricity trading

To prove that the system has certain practicality, the electricity transaction matching speed of the system was tested. Different numbers of users submit electricity information concurrently through 5 blockchain nodes. The average time required for the system to process each transaction was tested. The test results are shown in Fig. 5.

As can be seen from Fig. 5. When the total number of users is below 160, the system can complete about 0.35 electricity match per second, that is, each match takes about 2.86 seconds to complete. When the total number of users is above 160, the matching speed gradually decreases. When the total number of users is 120, and each node corresponds to 24 users, the matching speed of the system is the fastest, and the match of an electricity purchase demands is completed in about 2.38 seconds. The multi-factor matching mechanism of this system relies on all electricity sale demands. In the state of the same block height, the matching requests passed by each Peer endorsement are mutually exclusive. Therefore, when the number of users corresponding to each Peer node is excessive, the matching speed will be significantly reduced.

Supply ratio of clean energy

For the promotion of clean energy, the traditional mechanisms such as DA are used to match the same experimental data for electricity transactions, and the supply ratio of clean energy of the two matching mechanisms is compared. The result is shown in Fig. 6.

As can be seen from Fig. 6. In various test cases with the different volumes of users, the supply ratio of clean energy is about 78.15% by this system, while the supply ratio of clean energy is about 4.69% by traditional centralized matching mechanisms such as DA. This result fully proved that the system is conducive to promoting small-scale clean energy producers to actively participate in energy transactions in the REI, and promoting the development of clean energy and protecting the environment.

Total transmission loss

For the transmission loss caused by long-distance transmission, the traditional mechanisms such as DA are used to match the same experimental data for electricity transactions, and the total transmission loss of the two matching mechanisms is compared. The result is shown in Fig. 7.

As can be seen from Fig. 7. In various test cases with the different volumes of users, the average transmission loss rate of the total energy matched is 2.07% by this system, while the average transmission loss rate of the total energy matched is 3.15% by traditional centralized matching mechanisms such as DA. Therefore, the loss of energy transmission in the REI is reduced. This system has saved 1.08% of energy for the entire REI.

V. CONCLUSION

In this paper, a blockchain based distributed controllable electricity transaction matching system is designed and implemented for REI. The automatic match of a single transaction on the blockchain is implemented based on smart contract technology in this system, which avoids the interference of the number of transactions and the matching cycle on the matching speed of single transaction in the matching process. At the same time, the function of confirming matching records by private key signature is designed based on asymmetric cryptographic, so that the matching results are controlled by both parties to the electricity transaction. The system was tested experimentally in the application environment of the REI. The experimental results indicated that compared with traditional solutions, the supply proportion of clean energy in the entire REI increased from 4.69% to 78.15% in this system, and the electricity transmission loss in the entire REI is reduced by 1.08%.

REFERENCES

[1] A. Q. Huang, M. L. Crow, G. T. Heydt, J. Zheng, S. Dale, "The future renewable electric energy delivery and management (FREEDM) system: the Energy Internet," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 133-148, Jan.2011,doi: 10.1109/JPROC.2010.2081330.

[2] J. Cao, "The essence and implementation path of energy internet," *High Technology and Industrialization*, pp. 48-51, 2015.

[3] M. A. Hannan, M. Faisal, P. Ker, et al., "A review of internet of energy based building energy management systems: issues and recommendations," *IEEE Access*, vol. 6, pp. 38997-39014, 2018, doi: 10.1109/ACCESS.2018.2852811.

[4] J. Wang, K. Meng, J. Cao, Z. Chen, L. Gao, C. Lin, "A review of energy internet information technology research," *Computer Research and Development*, pp. 117-134, 2015.

[5] K. Yuan, J. Li, Y. Song, et al., "Summary and prospect of regional energy internet comprehensive evaluation technology," *Automation of Electric Power Systems*, vol. 43,no. 14, pp. 41-52+64, 2019.

[6] X, Zhou, R. Zeng, F. Gao, L. Qu, "Current status and prospect of energy internet development," *Scientia Sinica Informationis*, vol. 47, no.02, pp. 149-170, 2017.

[7] S. Chen, C. Liu, "From demand response to transactive energy: state of the art," *Modern Power Systems*, vol. 5, no. 1, pp. 10-19, January 2017, doi: 10.1007/s40565-016-0256-x.

[8] T. Haring, J. Mathieu, G. Andersson, "Comparing centralized and decentralized contract design enabling direct load control for reserves," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2044-2054, May 2016, doi: 10.1109/TPWRS.2015.2458302.

[9] B. Kim, S. Ren, M. van der Schaar and J. Lee, "Bidirectional energy trading and residential load scheduling with electric vehicles in the smart grid," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 7, pp. 1219-1234, July 2013, doi: 10.1109/JSAC.2013.130706.

[10] M. Vasirani, S. Ossowski, "Smart consumer load balancing: state of the art and an empirical evaluation in the Spanish electricity market," *Artificial Intelligence Review*, vol. 39, no. 1, pp. 81-95, 2013.

[11] Z. Y. Dong, F. Luo, G. Liang, "Blockchain: a secure, decentralized, trusted cyber infrastructure solution for future energy systems," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no.05, pp.118-127, 2018.

[12] O. Jogunola, A. Ikpehai, K. Anoh, et al., "State-of-the-art and prospects for peer-to-peer transaction-based energy system," *Energies*, 2017.

[13] E. Mengelkamp, J. Gärttnera, K. Rock et al., "Designing microgrid energy markets: a case study: the Brooklyn Microgrid," *Applied Energy*, pp. 870-880, 2018.

[14] S. Nakamoto, "Bitcoin: A peer-to-peer electronic cash system," *Technical report*, 2008.

[15] P. zaimang "Blockchain based decentralized management of demand response programs in smart energy grids, " *Sensors*, pp. 162, 2018.

[16] Z. Wu, Y. Liang, J. Kang, R. Yu, Z. He, "Secure data storage and sharing system based on consortium blockchain in smart grid," *Journal of Computer Applications*, vol. 37, no.10, pp. 2742-2747, 2017.

[17] Y. Yuan, F. Wang, "Blockchain: the state of the art and future trends," *Acta Automatica Sinica*, vol. 42, no.4, pp. 481-494, 2016.

[18] X. Tai, H. Sun, Q. Guo, "Blockchain-based power transaction and congestion management method in the Energy Internet," *Power System Technology*, vol. 40, no. 12, pp. 3630-3638, 2016.

[19] S. Bahrami, M. H. Amini, M. Shafiekhah, J. Catalao, "A decentralized electricity market scheme enabling demand response deployment," *IEEE Transactions on Power Systems*, vol. 33, no. 4, pp. 4218-4227, 2018.

[20] B. Li, Q. Qin, B. Qi, et al., "Summary of design of distributed energy trading scheme based on blockchain," *Power System Technology*, vol. 43, no. 3, pp. 961-972, 2019.

[21] E. Mengelkamp, B. Notheisen, C. Beer, D. Dauer, C. Weinhardt, "A blockchain-based smart grid: towards sustainable local energy markets," *Computer Science - Research and Development*, vol. 33, no.1, pp. 207-214, 2018.

[22] J. Wang, N. Zhou, Q. Wang, P. Wang, "Direct transaction mode and strategy of microgrid based on blockchain and continuous double auction mechanism," *Proceedings of the CSEE*, vol. 38, no.17, pp. 5072-5084+5304, 2018.

[23] S. Zhao, B. Wang, Y. Li, Y. Li, "Integrated energy transaction mechanisms based on blockchain technology," *Energies*, 2018.

[24] T. Morstyn, A. Teytelboym, M. Mcculloch, "Bilateral contract networks for peer-to-peer energy trading," *IEEE Transactions on Smart Grid*, vol. 10, no. 2, pp. 2026-2035, 2019.

[25] F. Luo, Z. Y. Dong, G. Liang, J. Murata, Z. Xu, "A distributed electricity trading system in active distribution networks based on multi-agent coalition and blockchain," *IEEE Transactions on Power Systems*, vol. 34, no. 5, pp. 4097-4108, 2019.

[26] S. Ai, D. Hu, J. Guo, J. Cao, “Multi-factor electricity transaction matching mechanism based on blockchain,” unpublished.

[27] S. Ai, D. Hu, T. Zhang, Y. Jiang, C. Rong, J. Cao, "Blockchain based power transaction asynchronous settlement system," in *2020 IEEE 91st Vehicular Technology Conf.*, pp. 1-6, 2020.

[28] E. Androulaki, A. Barger, V. Bortnikov, et al., "Hyperledger Fabric: a distributed operating system for permissioned blockchains," in *european conference on computer systems*, 2018.