PBFT-based Regional Energy Internet Blockchain Transaction Consensus

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Abstract*—Energy Internet interconnects a large number of energy nodes of various types of energy networks composed of distributed energy generating devices, distributed energy storage devices and various loads. It realizes two-way peer-to-peer energy exchanging and sharing network, which is an important application scenario of blockchain. As more producers and consumers join the energy Internet, a large number of consensus demands for energy transactions are generated. The consensus mechanisms widely adopted in the energy blockchains are generally hardly ensuring the effective development and conduct of transactions with the expansion of an energy Internet. In this paper, a regional energy Internet blockchain consensus mechanism based on the PBFT method is proposed for the distributed power transaction scenario. The mechanism selects consensus groups based on reputation, which reduces the probability of consensus group nodes appearing Byzantine nodes, and keeps away from the problem of excessive centralization of consensus group nodes caused by fixed consensus group nodes. Local, high-reputation nodes in a certain quantitative participate in consensus, avoiding the problem of reduced consensus efficiency caused by the increasing number of consensus nodes when the PBFT consensus mechanism is adopted. Multiple groups of consensus nodes participating in consensus concurrently could reduce the possibility of consensus nodes being attacked and eases the consensus pressure of fixed consensus group nodes. The scalability of the microgrid under the regional energy Internet scenario is improved. Experimental results confirmed the effectiveness of the proposed mechanism.

Keywords—Energy Internet, blockchain, energy transaction, consensus

I. INTRODUCTION

Energy Internet [1] is a comprehensive application of advanced electronic technology, information technology and intelligent management technology, which integrates a large number of distributed energy generating devices, distributed energy storage devices and various types of loads [2]. It realizes two-way peer-to-peer energy exchanging and sharing network.

As a rapidly developing technology, blockchain has the characteristics of distribution, equality, security, and traceability. It is highly compatible with the design ideas of the energy Internet [3]. Blockchain can be used as a viable technical basis for electricity transactions in the energy Internet to solve problems such as the decentralization of electricity transactions.

Consensus mechanism is a core part of the blockchain technology stack. Each blockchain node jointly maintains the accuracy and consistency of the recorded information through the consensus mechanism. The consensus mechanisms adopted by the existing researches of blockchain-based energy projects mainly include PoW, PoS, DPoS and PBFT, as well as consensus mechanisms improved on their basis [4,5].

As more producers and consumers join the energy Internet, especially for regional micro-networks with a large number of transaction nodes. The existing blockchain consensus mechanism may requires stronger competitiveness in the angles like consensus efficiency and consensus security, in order to facilitate the implementation of energy Internet blockchain applications. Existing consensus mechanisms applied in the energy Internet blockchains could be hard to avoid the problem of reduced consensus efficiency caused by the increase of consensus nodes.

In view of the actual construction of the energy Internet, the design of the consensus mechanism should consider factors such as the number of involved nodes, the degree of decentralization, data consistency, and consensus efficiency. In this paper, a blockchain consensus mechanism based on the PBFT method applied to the regional energy Internet is proposed. When the number of nodes continues to increase, it not only guarantees the consensus efficiency in the decentralized scenario, but also ensures the accuracy of the consensus results. At the same time, the scalability of the consensus mechanism also ensures the convenience of adding and exiting microgrids and nodes.

The rest of this paper is organized as follows. The current research status of consensus mechanisms in energy blockchains is briefly introduced in Section II. In Section III, the consensus mechanism proposed in this paper is given. The experimental results are provided in Section IV. Finally, this paper is summarized in Section V.

II. Related Works

Energy Internet is inherently distributed. It takes microgrids, distributed energy grids, smart communities, etc. as "local area network", large-scale power grid as "metropolitan area network", national or even larger scale power grid as "wide area network" [1,2]. In each sub-energy Internet architecture, energy nodes should be able to realize peer-to-peer trading to consume energy, especially renewable energy. Blockchain as a type of distributed ledger, could be qualified to support the distributed energy transactions in the energy Internet. Energy entities can ensure the consistency of energy transaction data through the blockchain consensus mechanism.

The consensus mechanisms adopted by the existing researches of blockchain-based energy projects mainly include PoW, PoS, DPoS, PBFT, and improved consensus based on them.

In the beginning, the focus of the consensus mechanism in energy blockchains is to ensure the consistency of node data in the distributed scenario. Conventional consensuses are adopted. Paper [6-8] mentioned adopting PoW to ensure the equality of each node's accounting and the consistency of node energy transaction data. However, PoW requires too much computation resource and causes energy consumption problems. Some studies attempt to improve PoW [9,10]. Nonetheless, the energy consumption problem is not yet solved fundamentally. Paper [11] proposed three PoS based consensus mechanisms for different energy transaction blockchains. Paper [12, 13] regards transaction volume and/or transaction amount as "stake" to improve PoS. Some studies, like [14,15], adopt DPoS consensus mechanism to sacrifice part of the degree of decentralization in exchange for consensus efficiency. However, in the studies above, either the transaction data are stored in separate chains, which increases the difficulty of storage space and data traceability, or the accumulation of "rights/interests" reduces the extent of decentralization of the system, easy to form super nodes. These could cause unequal rights between nodes, and may lead the energy Internet to degenerate into a centralized system. Studies attempt to use PBFT as the consensus mechanism with scenarios that energy nodes are equal and energy transactions are not relatively frequent. Normally, trusted nodes exist in the energy trading blockchain network of these scenarios [16,17]. In a microgrid without default trusted nodes, when the number of energy access entities increases, implementing the three-stage PBFT globally leads to a significant increase in node interactions. In addition, publicly determined trusted nodes are easy to be attacked.

Some other consensus mechanisms, for instance proof of authority (PoA), proof of elapsed time (PoET), fast probabilistic consensus (FPC), HashGraph, etc., would also be considered as competitive candidates for blockchain-based energy projects.

III. PBFT-based Regional Energy Internet Blockchain Transaction Consensus

In response to the aforementioned challenges, a blockchain consensus method based on the PBFT method applied to the regional energy Internet is proposed. It is a multi-level structure consensus for energy transaction blockchain, following the design idea of the multi-level architecture of "local area network"-" metropolitan area network"-"wide area network" of energy Internet. With the increasing number of nodes, it not only guarantees the consensus efficiency in the decentralized scenario, but also ensures the consensus result. At the same time, the scalability of the consensus mechanism also ensures the convenience of adding and exiting the microgrid.

The proposed consensus mechanism consists of the microgrid internal transaction consensus method and the microgrid external transaction consensus method. The energy Internet transaction scenario discussed in this paper is shown in Fig. 1.

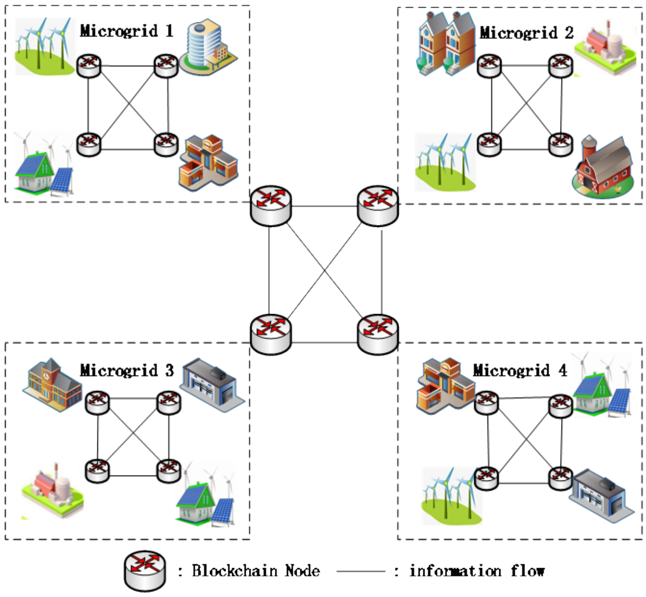

Fig. 1 The regional energy Internet scenario discussed in this paper.

A. *Consensus method for intra-microgrid transactions*

When both parties of the transaction are in the same microgrid, the microgrid internal transaction consensus method is adopted. The microgrid internal transaction consensus method consists of the following steps:

0) Initialization: All transaction nodes in the regional energy Internet initializing their reputation values

The reputation value refers to the integrity based on the historical data of the node's participation in the consensus, and is modified based on whether the node endorsement result is the same as the consensus result. The reputation value of all nodes has the same initial value (T_init) and upper limit (T_max). The reputation values are initialized and supervised by the supervisory nodes in the blockchain network. Once completed normally, the node's energy transaction consensus endorsement reputation value will increase by a fixed value (T_up); once the endorsement is wrong, the reputation value will decrease by a fixed value (T_down). Generally, $T\_down >> T\_up$. The reputation value does not increase after reaching the upper limit.

1) Selecting n microgrid internal nodes as consensus group nodes based on reputation value and random value

A consensus group composed of n (n>2) nodes will be temporarily established within the microgrid to record and distribute consensus. When a consensus group node is selected, a lower limit of reputation value (T_min) is adopted by all nodes, that is, only when the reputation value is higher than the lower limit, a node has the possibility to be selected as a consensus node. A random value (T_r) is also generated for each node whose reputation value achieves the standard, in order to increase randomness in the consensus group selecting. The random value has a certain range and is carried out under the supervision of all nodes or by the supervisory node. The trust value and the random value are added together, and the multiple nodes (n) with the highest values that have not participated in the transaction are identified as the consensus group.

2) The transaction initiating node signing the transaction record with a private key and broadcasting it to a consensus group node

The transaction initiation node is the power purchase node. The purchase node needs to communicate with the sales node on-chain or off-chain in advance. After the two parties agree to the transaction, the purchase node obtains the signature of the sales node and generates an energy transaction record. A feasible way of on-chain communication is provided in Paper [3]. The purchase node serves as the transaction initiation node to broadcast the energy transaction record to a consensus group node. The specific information includes at least: transaction record ID, electricity purchase user ID, electricity seller ID, electricity purchaser's private key signature, electricity seller's private key signature, transaction unit price, transaction volume, and transaction amount.

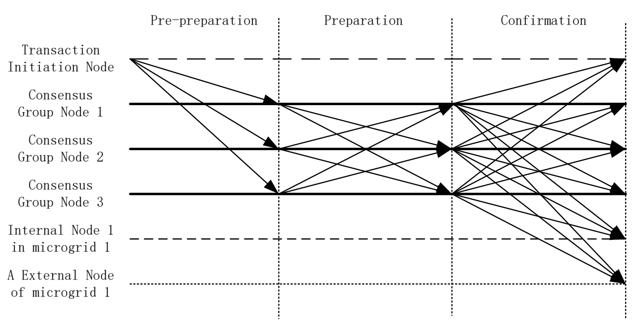

Fig. 2 Consensus verification for intra-microgrid transactions.

3) Consensus group nodes performing Byzantine consensus verification on the received energy transaction records

Consensus verification mainly includes three stages: pre-preparation, preparation, and confirmation, as shown in Fig. 2.

In the pre-preparation stage, the transaction initiating node sends the energy transaction record to the consensus group nodes. The consensus group node verifies the private key signature in the energy transaction record and the transaction amount. After the verification is passed, the energy transaction record is endorsed.

In the preparation stage, the consensus group node sends the endorsed energy transaction records to the consensus group nodes other than itself, and the consensus group node verifies the collected endorsed energy transaction records. If the number of endorsed records received is greater than $2m$+1 ($\exists m \in \boldsymbol{N}, \mathbf{s.t.}\, 3m+1 \geq n$), a consensus result message corresponding to the energy transaction record is generated.

In the confirmation stage, the consensus group nodes broadcast the consensus result message to all nodes in the regional energy Internet except themselves, and all nodes make consensus result judgments based on the received consensus result message. If the number of result messages of the consensus group collected by each node is greater than a certain ratio, we adopt $n/2$ in this paper, it is determined to be a correct message. Then the energy transaction record is stored in the local blockchain.

4) All nodes modifying the reputation value of the consensus group node in the local reputation value list

All nodes update their reputation value list according to the preset and received message results. The reputation value of the consensus group node that has completed the consensus normally increases by T_up. The reputation value of the consensus group node that could not complete the consensus is reduced by T_down.

B. Consensus method for inter-microgrid transactions

When the parties of a transaction are not in the same microgrid, the microgrid external transaction consensus method is adopted. The microgrid external transaction consensus method consists of the following steps:

1) Selecting n nodes in the microgrids involved in the transactions as consensus group nodes based on reputation value and random value

According to the reputation value and random value, n nodes are selected from multiple microgrids participating in the transaction as consensus group nodes. The consensus group nodes for external transactions of the microgrid are composed of all the top n nodes selected by the sum of the reputation value and the random value from the multiple microgrids participating in the transaction, and the nodes participating in the transaction cannot enter the consensus group.

2) The transaction initiating node signing the transaction record with the private key and broadcasts it to the consensus group node, similar to the consensus method for intra-microgrid transactions

3) The consensus group performing Byzantine consensus verification on the received energy transaction records, *similar to the consensus method for intra-microgrid transaction*

4) The nodes of the consensus group broadcasting the consensus result message to all nodes except themselves in the regional energy Internet, as illustrated in Fig. 3.

5) All nodes modifying the reputation value of the consensus group node in the local reputation value list, similar to the consensus method for intra-microgrid transaction

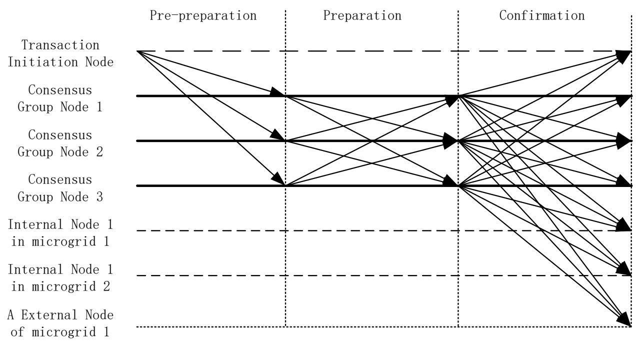

Fig. 3 Consensus verification for inter-microgrid transactions

According to the actual design framework of power and other energy sources, the internal nodes of a microgrid have more frequent transactions with the internal nodes of this microgrid. The transactions between nodes from different microgrids are less frequent. The proposed mechanism can still control the scale of consensus within a certain range under the condition of network expansion, reduce unnecessary consensus preparation, communication and confirmation stage, and improve consensus efficiency.

IV. Experimental Results

The experimental equipment of this work is a Lenovo Xiaoxin Air 14 2020 notebook with Intel(R) Core(TM) i5-1035G1 CPU and 16GB RAM. Golang language multi-coroutine concurrency technology is adopted to realize the consensus mechanism and to simulate multiple clients and server nodes performing consensus verification of blockchain transactions. In the experiments, a client node corresponds to the client terminal in the blockchain network, which is used to initiate blockchain transactions. A server node corresponds to the consensus node in the consensus process. It should be noted that, in order to conduct performance experiments, the server node and the client node are set respectively. However, it is not necessary to set a server node and a client node separately, when using the consensus mechanism proposed in this paper. That is, in actual implementation, the server node and the client node can be deployed in the same server/device. The results of each experiment are the average of multiple tests.

Aiming at the current consensus mechanism of the regional energy Internet scenario, as the number of consensus nodes increases and the consensus efficiency is significantly reduced, an experiment with a gradual increase in consensus nodes is carried out.

In this experiment, the regional energy Internet is divided into 10 microgrids, each microgrid corresponds to 2 client nodes, the initial value of the server node is 50, that is, each microgrid corresponds to 5 server nodes, and each test increases by 10 The number of server nodes is evenly increased in 10 microgrids, with a maximum of 200 server nodes. The server Byzantine error rate is set as 10%. The number of nodes in a consensus group is set as 4. The throughput calculation formula is shown in equation (1). The experimental test results are shown in Fig. 4.

$$Throughput = \frac{Number\ of\ transactions\ correctly\ agreed}{Time\ of\ achieving\ consensus} \tag{1}$$

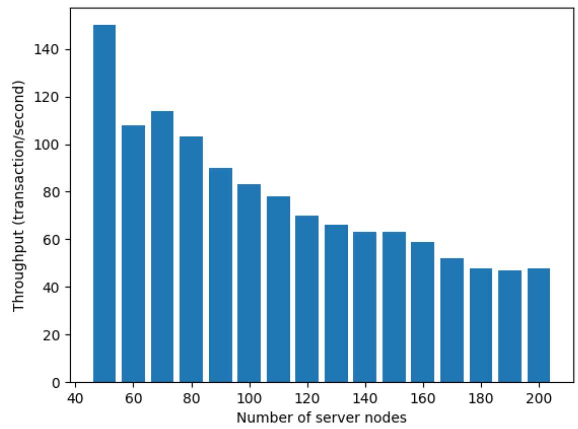

Fig. 4 The relationship between blockchain throughput and the number of server nodes.

It can be illustrated from Fig. 4 that the throughput of blockchain consensus decreases with the increase of microgrid service end nodes. Firstly, the consensus efficiency shows a linear-like downward trend when the number of nodes increases. While the network size increased close to 180 nodes, the downward trend stops and shows a stable tendency. This phenomenon is in line with the design feature of the proposed consensus mechanism, in which the consensus scale is controlled to a certain scale to provide more flexible scalability for the energy Internet transaction network.

In order to test the consensus efficiency of concurrent consensus of multiple groups of consensus nodes, an experimental test of concurrent consensus among multiple groups of consensus nodes is conducted.

In this experiment, the number of microgrid is set as 1. The initial value of client nodes is 10, all client nodes belong to the same microgrid, each client transaction selects a different consensus group node for consensus, and then 10 clients nodes are added to each test. The maximum value of client nodes is 200, and the number of server nodes is set unchanged as 100. The server Byzantine error rate is 10%. The number of nodes in a consensus group is set as 4. The throughput calculation formula is shown in equation (1). The experimental test results are shown in Fig. 5.

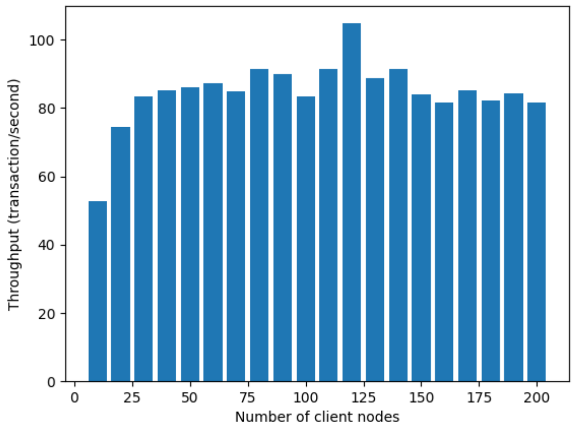

Fig. 5 The relationship between blockchain throughput and the number of client nodes.

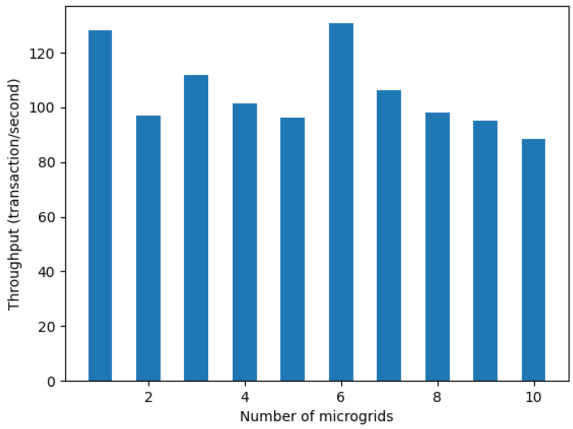

Fig. 6 The relationship between blockchain throughput and the number of microgrids.

It can be demonstrated from Fig. 5 that, when the number of client nodes is less (when the number of client nodes is 10 or 20), the throughput gradually increases as the number of client nodes increases, which is as expected. When the quantity of client nodes is higher than 30 client nodes, the throughput is at a relatively stable level. The values of individual bars may be due to the limited number of the tests, which does not essentially affect the general stability of the consensus efficiency while client nodes increasing. The generally stable throughput could imply that the consensus efficiency of the proposed consensus mechanism is relatively stable, in the situation of concurrent consensus among multiple groups of consensus nodes. Such a consensus mechanism is of significance to the stable execution of energy blockchain transactions in the energy Internet.

In view of multiple microgrids with intra-microgrid transactions, the impact of microgrid quantity increasing on the performance of the consensus mechanism is tested by observing the change in throughput while the microgrid expanding.

In this experiment, the number of microgrids is set from 1 to 10. Each microgrid contains 10 server nodes. The initial value of the number of server nodes is 10. Each test adds 10 server nodes, which belong to the same microgrid, which means that a new one has been expanded. In each microgrid, the number of client nodes remains unchanged as 20. The server Byzantine error rate is 10%. The number of nodes in a consensus group is set as 4. The throughput calculation formula is shown in equation (1). The experimental test results are shown in Fig. 6.

As shown in Figure 6, although the throughput of microgrids has a certain level fluctuating, they basically show a steady state. It can be considered that the increasing of microgrid quantity has a limited impact on the efficiency of the autonomous consensus on internal transactions of multiple microgrids proposed in this paper. It could verify that the proposed consensus mechanism provided optimistic scalability of microgrids in regional energy Internet.

In the throughput experiments of Fig. 4, Fig. 5, and Fig. 6, a certain amount of instability has appeared. The source of this phenomenon may be due to the limitation of the scale of the experiments and the number of tests. A certain degree of uncertainty is likely to occur when the sample size is insufficient. At the same time, the fluctuation of throughput in the above experiments may also originate from one or more reasons that have not been illustrated, which affects the results of the experiment. According to the experimental platform and development cycle of this study, exploring these reasons will be considered as part of our future work.

When the number of energy blockchain nodes is certain, in order to obtain a division of the number of microgrids that are more suitable for this consensus mechanism, a comparative experiment test of client delay under different divisions is carried out. The client delay measurement standard is set as the client submits a transaction request to the customer The time it took for the terminal to receive confirmation of the transaction request.

In this experiment, the number of microgrids is set from 1 to 10. The number of server nodes remains unchanged at 100. That is, different microgrid divisions correspond to 100 server nodes. The initial value of the number of client nodes is 10, and each test adds 10 client nodes. The server Byzantine error rate is 10%. The number of nodes in a consensus group is set as 4. The experimental test results are shown in Fig. 7.

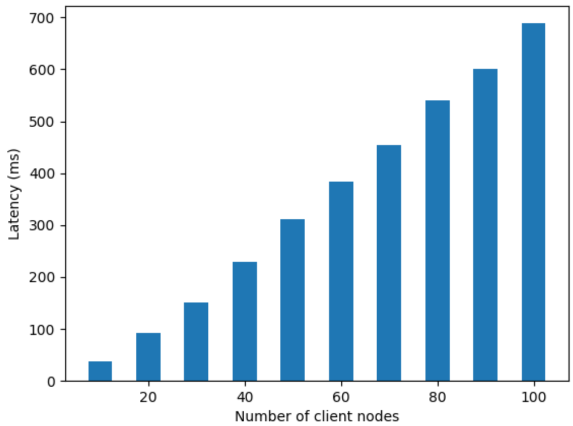

Fig. 7 The relationship between client latency and the number of clients.

It can be seen from Fig. 7, when the number of server nodes is constant, the average delay of consensus increases with the number of microgrids (the number of clients). This is in line with the characteristics of the proposed consensus mechanism, latency increases as the number of transactions increases. In addition, the increase is not exponential-like, but linear-like. This could imply that the energy blockchain adopting the proposed consensus mechanism can have higher scalability, compared to the blockchains which adopt consensus mechanisms with exponentially grown delays.

V. Conclusion

In this paper, a regional energy Internet blockchain consensus mechanism based on the PBFT method is proposed for the distributed power transaction scenario. The mechanism selects consensus groups based on reputation, which reduces the probability of consensus group nodes appearing Byzantine nodes, and keeps away from the problem of excessive centralization of consensus group nodes caused by fixed consensus group nodes. Local, high-reputation nodes in a certain quantitative participate in consensus, avoiding the problem of reduced consensus efficiency caused by the increasing number of consensus nodes when the PBFT consensus mechanism is adopted. Multiple groups of consensus nodes participating in consensus concurrently could reduce the possibility of consensus nodes being attacked and eases the consensus pressure of fixed consensus group nodes. The scalability of the microgrid under the regional energy Internet scenario is improved. Experimental results confirmed the effectiveness of the proposed mechanism.

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