Research on Typical Architecture and Application of Distribution Internet of Things Based on Blockchain

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Abstract. The new round of energy reform is marked by large-scale development and utilization of new energy and re-electrification as the fundamental path, to cope with the pressure of absorbing renewable energy and stupendous access to variable loads such as electric vehicle charging piles creates several problems such as a large number of equipment failure and low standardization in the distribution network, to overcome this, the distribution Internet of Things (D-IoT) came into existence. In this paper an equivalent architecture of blockchain and D-IoT is built based on master-slave multi-chain. The combined equivalent architecture proposes the crucial application of blockchain technologies as consensus mechanism and smart contract in the D-IoT in order to explore the broad application prospects of blockchain in the D-IoT.

1. Introduction

The distribution network of power system comprises of large number of various equipment. At the same time, the topology involved is relatively complicated. These characteristics bring great challenges to the management of the distribution network. Based on the above background, the distribution Internet of Things (D-IoT) came into existence creating a new reformation of power network generated by the deep integration of traditional technology and the Internet of Things (IoT) technology. Through comprehensive interconnection, intercommunication, and interoperation between distribution networks equipment, realizes comprehensive distribution network data perception, data fusion, and intelligent applications. And it meets the lean management requirements of the distribution network, supports the rapid development of the energy internet, and forms the advanced distribution network in the new generation of power system. In terms of the application form, the application of D-IoT has the characteristics of terminal plug and play, extensive equipment interconnection, comprehensive status awareness, application mode upgrade, rapid business iteration, and efficient resource utilization.

D-IoT has the characteristics of “multi-hop, interconnection, autonomy, self-healing”, which is naturally similar to the distributed, weakly centralized operation mode, topology, and coordination mechanism of the blockchain. The combination of these two can support the construction of the D-IoT well. Ref. [1] mentions the overall architecture, concepts, and characteristics of the construction of the D-IoT, and explains the key technologies involved in the D-IoT. Ref. [2] mentions the integration of 5G with the ubiquitous power Internet of Things, analyses specific application scenarios, and summarizes the key technologies. Ref. [3] mentions the application of edge computing in D-IoT,
realizing lightweight data processing on the spot, and solving the huge pressure on the master station caused by the transmission and calculation of massive heterogeneous data.

The above literatures analyses the new features faced by the D-IoT in the construction and application of power systems, namely interconnection, cloud-side collaboration, terminal collaboration, regional autonomy, distributed decision-making, planar management, and intelligent collaboration. It proposes 5G, edge computing, blockchain, mobile internet, artificial intelligence, and other technologies supporting D-IoT, but it does not discuss the integration mode of D-IoT and blockchain technology deeply. In particular, there is no close combination of the similarities between the D-IoT and the blockchain to study the application scenarios of the blockchain in the D-IoT. Therefore, this paper aims at the requisite of intelligent coordination, regional autonomy, distributed decision-making, and planar management of D-IoT “cloud, channel, edge, and terminal”, based on the D-IoT and the similar network topology of the blockchain, studies the equivalent models of D-IoT and the blockchain, analyses the typical architecture and operating mechanism of the D-IoT enhanced by the blockchain building a flexible, autonomous, and regionally autonomous technology system for the D-IoT under weak centralization.

2. Equivalent Architecture of Blockchain and Distribution Internet of Things

The blockchain and the D-IoT have natural similarities in many respects, and both have the characteristics of weak centralization and similar topological structures. The integration of the two can be achieved from the perspective of the combination of blockchain and D-IoT, mapping the blockchain nodes to important nodes in the D-IoT, and constructing an equivalent architecture of blockchain and D-IoT. Due to the differences between nodes in the D-IoT, it is impossible to maintain consistent computing and storage capabilities, so the nodes are distinguished and corresponds to the nodes on the blockchain. Based on the mapping relationship between the nodes, and the D-IoT requires massive data interconnection and other factors, and considering frequent data interactions have hidden security risks, the D-IoT can be equivalent to the master-slave multi-chain structure. The master chain is composed of important nodes in the D-IoT. The master chain is responsible for verification, query, and issuance of control commands, routing decisions, and other functions. Among them, verification includes verification of generated blocks and micro-grid transactions; the slave chain is responsible for transmitting data to the master chain, accepting the command information issued by the master chain to cooperate with the master chain to accomplish the task.

Equation (1) introduces the concept of node importance from the perspective of node relevance, computing power, etc.

\[ NI_s = \omega R_s + \varphi C_s + \tau S_s \]  

where, \( \omega, \varphi, \tau \) are the weight values of various indicators, which can be set according to the actual situation. \( R_s \) represents the node relevance, to measure the number of nodes in the area with the node \( s \) and indirectly evaluate its importance. \( R_s \) is represented by equation (2).

\[ R_s = \frac{1}{2}(q_{in} + q_{out}) \]  

where \( q_{in} \) is the node access volume and \( q_{out} \) is the node output volume.

\( C_s \) represents the computing power of the node, which is also a key factor to measure the importance of the node. The node parameter with strong computing power can be set to 5, and the node parameter without computing power is set to 0.

\( S_s \) indicates the storage capacity of the node, similar to the computing power, the range is set between [0, 5].

Finally, the importance of the nodes is normalized to facilitate the division of the nodes and is represented by equation (3).

\[ NI_s' = k \frac{NI_s - \min NI}{\max NI - \min NI} \]
After dividing the nodes by the above method, the important nodes constitute the master chain, and the remaining nodes form the slave chain, thereby constructing a D-IoT architecture based on the master-slave multi-chain, as shown in figure 1.

![Figure 1. Equivalent architecture.](image)

3. Application of Consensus Mechanism in Distribution Internet of Things

The concept of D-IoT includes four levels: cloud, channel, edge, and terminal. "Cloud" refers to the construction of the main distribution station in the cloud which realizes multiple functions such as power distribution terminal management, equipment status monitoring, power supply command, and risk warning in the cloud. “Terminal” refers to the intelligent distribution terminal, reducing the type of terminal and reducing the difficulty of maintenance, which involves environmental perception, electrical measurement, energy collection, etc. The “Channel” is the bridge connecting the “cloud” and "terminal". The blockchain is unique for data tamper resistance, traceability, and other aspects, ensuring data security to the greatest extent. However, if new nodes are added to the D-IoT, it is necessary to consider whether the access node is malicious and whether it will cause damage to the entire network or not. The consensus mechanism can achieve the verification of the security of new access nodes through higher efficiency and lower cost.

When a power distribution terminal wants to access the D-IoT based on a master-slave multi-chain architecture, first register with the master station in the cloud and package the power distribution terminal information, such as terminal functions and energy consumption, into the blockchain. It is convenient for other nodes to query. In the packaging process, the public key is used for encryption, and the node needs to use the private key for the query. At the same time, the broadcast function of the blockchain is used to broadcast to the nodes on the master chain. After receiving the information, the nodes on the master chain use a consensus mechanism to negotiate whether to grant access to the terminal. After reaching a consensus, the results are distributed to the slave chain, thereby ensuring the security of new node access.

Due to the numerous characteristics of the distribution network nodes, all nodes participate in the consensus process with low efficiency. Therefore, combining the importance of the nodes, select the nodes with higher importance to complete the process. We choose the Improved Byzantine Fault Tolerance (IBFT) consensus mechanism. IBFT refers to the improvement of Practical Byzantine Fault Tolerance Algorithm (PBFT), which not only improves efficiency but also effectively prevents malicious node access. IBFT expands itself based on PBFT and can achieve a synchronous consensus of 200 nodes. It simplifies the communication path and reduces the communication complexity. The IBFT mechanism is to select several master nodes and several slave nodes from all nodes. When a node sends a request to the master node, the master node broadcasts to other nodes. After receiving the
message, other nodes make feedback and use the slave node to collect each round of voting. When the number of collected signatures reaches the threshold, sending an execution message to the requesting node and each node is equivalent to reaching consensus.

The verification process of the consensus mechanism is as follows: First set up the node situation set, including the node address, node classification, node status, function, and other information in this data set, and pack the node situation set into the blockchain. Then combine the node importance to select the master node, slave node, and light node. The master node is the main body participating in the consensus, and all master nodes participate in the voting to make decisions. The slave node is a node of higher importance in the slave chain, which plays the role of collecting votes and sending messages, reducing the pressure of the master node. Light nodes are generally ordinary nodes without computing and storage capabilities.

When a new node requests access, the cloud master station broadcasts to all master nodes. The master node makes an analysis and votes according to the node situation set, and the slave nodes collect the votes. When the collected votes reach the threshold, execution information is sent to all nodes, the consensus is reached, and after the consensus is completed, the node situation set needs to be updated. The consensus process of new nodes joining is shown in figure 2.

![Figure 2. New node joining process.](image)

In the entire process, the number of data interactions is only a multiple of n, so the arithmetic complexity is only O(n), and the hardware requirements are not high, which means that the limit on the computing power of the node is reduced.

If during the consensus process, it is found that a node is not suitable for access or there is a security risk, it will record the information of the node on the node situation set on the chain and notify the cloud master station to refuse this node to access again, reducing the pressure of the master node and reducing the risk.

Of course, this also involves a situation where special circumstances such as the failure of the master node affect the consensus mechanism. In IBFT, if the master node that does not work normally does not exceed 1/3, the consensus process can still run normally. And if the slave node finds that it has not received the information of a certain node, it broadcasts to the power distribution master station after the consensus process is completed. After the master station verifies that it needs maintenance, it uses the characteristics of the IoT to temporarily replace it by the neighboring master node. If you need to replace it, select a node from the slave nodes to replace it according to the parameters such as the importance of the node.

4. Application of Smart Contract in Distribution Internet of Things
Nowadays, with the high proportion of distributed power sources, electric vehicle charging piles and other variable load access have a huge impact on the distribution network, at the same time, due to the characteristics of strong randomness and a large number, it also causes difficulties for power system
4.1. Micro-grid Transaction

The purpose of the micro-grid is to achieve flexible and efficient use of distributed power sources and solve a large number of grid-connected problems. The micro-grid is equivalent to a small power grid composed of distributed power sources, energy storage devices, energy conversion devices, related loads, monitoring, and protection devices. In the D-IoT, the micro-grid is regarded as a node.

However, because the micro-grid is both a load and a power generator, it poses challenges to the safe and efficient management of the micro-grid in the D-IoT. The smart contract in the blockchain can greatly shorten the reaction time and speed up the response speed, and it also has flexible deployment capabilities, which can modify the contract content at any time according to actual needs. When the electricity sales company and micro-grid users reach a relevant agreement, the agreement is deployed in the form of a smart contract in the blockchain. When the preset conditions are triggered, the smart contract will make a judgment to make a relevant response and write it into the blockchain [4-5].

First of all, it is necessary to establish a mathematical model for photovoltaic power generation, wind power generation, and other power generation methods in the micro-grid, and combine the environmental parameters obtained by the D-IoT to predict its power generation accompanying the following equations.

\[ P_{el} = f(P_u, w, s, D_t) \]  
\[ P_{pv} = \gamma g(L_r, L_a) \]  
\[ P_w = \gamma h(W_s, W_d, W_h) \]

where, \( P_{el} \), \( P_{pv} \), and \( P_w \) represent the predicted values of load, photovoltaic power generation, and wind power generation, respectively. The load forecast is affected by historical electricity consumption \( P_u \), meteorological data \( w \), season \( s \), and date type \( D_t \); photovoltaic power generation is affected by solar radiation \( L_r \) and angle \( L_a \); the amount of wind electricity generated is affected by wind speed \( W_s \), direction \( W_d \), and duration \( W_h \), and \( \gamma \) is the loss rate.

After obtaining the predicted amount in the micro-grid, the smart contract operation process combined with the scenario in figure 3 is as follows:

![Figure 3. Micro-grid transaction scenario.](image)
When the power generation in the micro-grid is less than the power consumption, check whether there is still a power reserve in the energy storage device. If the demand cannot be met, first consider whether there is remaining power generation in other micro-grids. The electricity price is determined according to the actual cost and loss. If the demand cannot be met, power is delivered from the power grid, and the electricity price of these energies is charged according to the normal electricity price; when the power generation in the micro-grid is more than the power consumption, there are two ways to deal with the remaining power. The first is that the power quality meets the standard and the power flow of the large power grid is acceptable. The remaining power is returned to the power grid nearby. The actual cost depends on the possible losses. The second is due to various reasons. The large power grid does not receive the micro-grid return, and the remaining can be stored in the energy storage device for future use.

When the power generation amount is greater than the actual power consumption, it is also necessary to consider the ranking of distributed energy based on user preferences and other indicators. The power generation unit with a higher priority first supplies power to the user. The formula for calculating the node priority is as follows:

\[ L_i = m \alpha_i + n \beta_i + o \gamma_i + p \epsilon_i \]  \hspace{1cm} (7)

where, \( m, n, o, p \) represents the weight of the relevant index, which can be adjusted according to the actual situation.

\( \alpha_i \) represents the power supply type index numbered \( i \). For example, the weight of wind power is set to 3, and photovoltaic power generation and energy storage equipment are set to 2 and 1.

\( \beta_i \) represents the available power index, in which the power generation of wind farms and photovoltaic power plants is calculated according to the annual average of the actual power generation capacity, and the energy storage equipment is calculated based on the average historical energy storage.

\( \gamma_i \) represents the power supply cost index, that is, the amount of electricity consumed by the power generation unit numbered \( i \) for each degree of electricity supplied.

\[ \gamma_i = \frac{M_{\text{total cost}}}{P_{\text{total power}}} \]  \hspace{1cm} (8)

\( \epsilon_i \) represents the user’s evaluation index of the power supply unit numbered \( i \), and the user evaluates the power supply unit that provides the service.

To ensure that the value range of the relevant index is fixed, the following processing needs to be done (where \( c \) can be set according to the actual value range):

\[ y_i = c \frac{y_i}{y_{\text{max}}} \]  \hspace{1cm} (9)

When the above transaction is completed, transaction information and transaction process is written into the blockchain to ensure transaction transparency.

4.2. Electric Vehicle Energy Transaction

Smart contracts can also be applied to electric vehicle electrical energy trading, because electric vehicles are relatively random loads, and a large number of access will destroy the stability of the distribution network, but as a load with high flexibility, if the charging pile is properly arranged, it can play the role of cutting peaks and filling valleys and improve the utilization rate of electric energy [6-8].

Electric vehicles can be regarded as movable nodes in the D-IoT. The electric vehicle company will give each electric vehicle a unique number and record it with the electricity sales company so that it can be recorded on the blockchain when the electric vehicle is charging. Combined with the comprehensive perception of the situation in the D-IoT, you can know that there is less electricity load in a certain area, and use the rapid response advantages of smart contracts in the blockchain to rationally arrange the charging of electric vehicles.
The specific operation process of the smart contract is as follows: First, when the electric vehicle issues a demand for charging, the preset conditions are triggered; the smart contract responds according to the agreement signed by the electricity sales company, the user, and the charging pile manager. It mainly provides discounts for electric vehicle users based on factors such as the remaining mileage of the electric vehicle, the load situation in the nearest area, and waiting time; after the transaction is completed, the transaction information and electric vehicle number are packaged into the blockchain to achieve transaction transparency and data tamper resistance.

Among them, according to the request, 90% of the remaining mileage of the electric vehicle is used as the radius, looking for the charging pile in the area with less power consumption, and calculating the discount based on the factors such as distance and waiting time. This not only reduces the impact on the distribution network but also improves the power utilization rate.

5. Other Applications of Blockchain in Distribution Internet of Things

Various communication methods are involved in the communication link of the D-IoT, such as NB-IoT, LoRa wireless, and each communication method uses different protocols when transmitting data, which also causes the protocol conversion must be performed first when data analysis is performed and then it becomes a unified format, which increases a lot of work. In the equivalent architecture of D-IoT based on blockchain, the protocol conversion script is written into it. When data is uploaded from the chain, the data format is unified by the script and then uploaded to the master chain, reducing the workload of subsequent merged data.

At the same time, there is also a common problem of the IoT in the D-IoT, which is the routing problem. In consideration of many factors such as path length and energy consumption, the optimal route is selected and mapped to the D-IoT based on the master-slave multi-chain. The nodes on the slave chain upload data according to which path and the nodes on the master chain are responsible for issuing instructions and broadcasting consensus results to those nodes. To solve the above problems, the routing strategy can be written into a script and added to the blockchain. The node obtains the best path through the script and packages it in the blockchain. If the data is found to be distorted or lost during the data transmission process, the fault point can be found based on the record, thereby ensuring the safety and integrity of the data transmission.

6. Conclusion

This paper specially focuses on the similarities between the D-IoT and the blockchain. Based on the master-slave multi-chain structure, the equivalent architecture of the D-IoT and the blockchain is built, and the application scenarios of consensus mechanism and smart contract based on equivalent architecture are analysed. With the integration of blockchain technology, the D-IoT has realized the security coordination between nodes and the efficient and transparent transaction of electrical energy. It concludes that the integration of blockchain and D-IoT has broad prospects for security enhancement and ease of network operation.

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References

[1] Lv J, Sheng W, Liu R, Wang P, Lu G, Lin J and Zhang Z 2019 Design and application of distribution internet of things High Voltage Engineering 45 (06) 1681-1688.
[2] Wang Y, Chen Q, Zhang N, Feng C, Teng F, Sun M and Kang C 2019 Fusion of the 5G communication and the ubiquitous power internet of things: Application analysis and research prospects Power System Technology 43 (05) 1575-1585.
[3] Sun H, Zhang J, Wang P, Lin J, Guo F and Chen L 2019 Edge computation technology based on distribution internet of things Power System Technology 43 (12) 4314-4321.
[4] Rana M M and Li L 2015 Microgrid state estimation and control for smart grid and Internet of Things communication network Electronics Letters 51 (2) 149-151.

[5] Han S, Gu M, Yang B, Lin J, Hong H and Kong M 2019 A secure trust-based key distribution with self-healing for internet of things IEEE Access 7 114060-114076.

[6] Duan B, Xin K and Zhong Y 2020 optimal dispatching of electric vehicles based on smart contract and internet of things IEEE Access 8 9630-9639.

[7] Hu W, Yao W, Hu Y and Li H 2019 Collaborative optimization of distributed scheduling based on blockchain consensus mechanism considering battery-swap stations of electric vehicles IEEE Access 7 137959-137967.

[8] Sheikh A, Kamuni V, Urooj A, Wagh S, Singh N and Patel D 2019 Secured energy trading using byzantine-based blockchain consensus IEEE Access 8 8554-8571.