Research on Micro-Grid Electric Energy Transaction Mechanism Based on Master-Slave Smart Contract

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***Abstract*—In view of the increasing generation of the distributed generation system, the increasing randomness and intermittence of micro-grid have been attracted much attention. The complexity and decentralization of power status information, which is difficult to meet the needs of the current power market in the stability and efficiency of the grid transaction. According to the randomness and intermittent characteristics of distributed generation, this paper innovatively proposes a micro-grid electric energy transaction mechanism based on Master-Slave smart contract and designs a framework of the Cyber-Physical System (CPS) for micro-grid. The specific constraints of micro-grid topology are analyzed. And in the cloud platform, smart contracts are used to reasonably manage the transaction order when the stochasticity of distributed generation generates excess or insufficient electricity.**

***Keywords*—Distributed power generation, Electric power transaction, Real-time price, Smart contract.**

I. Introduction

The decrease of fossil energy and environmental problems have been attracted much attention. The demand for electricity consumption of users is growing rapidly with the development of economy. Distributed Generation (DG) technology using renewable clean energy has been valued and developed. However, renewable energy is overly dependent on the external environment, so it has the characteristics of strong randomness and intermittent. The output of DG is unstable and uncontrollable [1]. DG has a large impact on the large power grid when it is connected to the grid. The form of micro-grid can solve the problem of grid connection and reduce the difficulty of operation and maintenance.

With the continuous progress of electric power science and technology, the internet and smart grid have been built and developed. Using internet technology can coordinate and manage all aspects of energy system [2]. With the release of a series of national policies, micro-grid can supply power directly to the users in the power grid. Customers and sellers are allowed to reach a long-term agreement and negotiate their own price system while trading. It is suggested that distributed energy can be used to reduce the electricity price. The energy can be stored and released flexibly by means of cloud energy storage, and the corresponding mathematical model is given [3]. Micro-grid is also developing in the direction of intelligence, commercialization, and marketization. Some scholars have studied the distributed micro-grid blockchain technology, designed the transaction system framework for micro-grid power market, and tried to build a blockchain-based trading model [4]. At present, micro-grid is mainly used as an independent operating individual in the power market to realize the transaction strategy between multiple parties. However, as the micro-grid transaction is short-term and uncertain compared with the large power grid transaction, the trading data lacks security and is easy to form a data island. This will lead to inefficient trading. Obviously, the market operation management mechanism is immature.

Blockchain technology has the characteristics of decentralization which can solve the trust problem between the two sides of the transaction [5]. The data of blockchain can’t be changed once produced. It initially established a secure and reliable digital monetary mechanism in the financial field. The appearance of smart contracts has extended blockchain technology to more scenarios. Blockchain technology provides a transparent, open and credible solution for power transaction system. Brooklyn, New York, has successfully set up a small-scale micro-grid power supply platform based on Ethereum that represents the direction of future community energy development [6]. At the same time, the energy transaction market framework, transaction system and optimal scheduling under the blockchain mechanism have been widely discussed.

In this paper, a micro-grid electric energy transaction mechanism based on Master-Slave Smart Contract is proposed. Firstly, the Cyber-Physical Systems (CPS) is constructed. It monitors and collects the system data. And then construct the real-time price (RTP) model of the power trading system based on the two-part tariff. Secondly, DG smart nodes create transactions and sign smart contracts according to an actual supply-demand relationship. Finally, most of nodes in the network reach a consensus on the transaction information. The power market transaction cloud platform automatically executes the contract content and writes the trading data into a blockchain to save.

II. CONSTRUCTION OF MICRO-GRID CPS

The micro-grid CPS integrates power system and network communication. The micro-grid CPS includes the physical network topology of micro-grid user side, communication network terminal equipment, and the power market transaction cloud platform. Fig. 1 is the framework of micro-grid CPS.

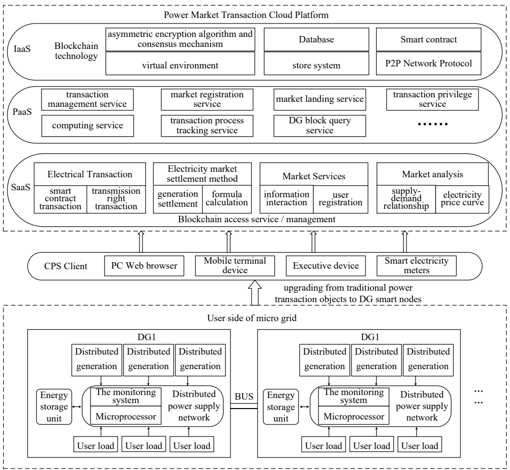

Figure 1. Framework of CPS for micro-grid

1) Micro-grid user layer: the physical network topology usually consists of distributed generation unit, energy storage unit, user load, monitoring management system, and power lines. The monitoring management system can realize the function of information extraction, understanding and prediction by collecting and analyzing data. The data is transmitted to the power market transaction cloud platform through the communication interface. The interconnection of information and cloud platform can provide reliable data and effectively prevent the formation of data islands for power transactions.

2) Client layer: users can register the power market transaction cloud platform with various terminal devices, that means upgrading from traditional power transaction objects to DG smart nodes. Internet technology can provide users with a variety of services and interaction methods.

3) Power market transaction cloud platform: the platform includes Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS). IaaS is supported by the underlying technology of Blockchain. It includes asymmetric encryption algorithm and consensus mechanism. And it configures virtual environment. Database is introduced for distributed massive storage and high-performance parallel computing. IaaS builds a basic operating environment for power trading. And it realizes Peer-to-Peer (P2P) transaction. PaaS uses platform bus to realize diversified interaction between DG smart nodes and cloud platform, it provides comprehensive management services such as registration, tracking of orders, permissions, etc. Based on the special needs of the power market, SaaS provides information on four aspects: market transaction, market settlement, market service, and market analysis.

III. THE RTP CALCULATION METHOD BASED ON TWO-PART TARIFF

Natural resources have different distributions depending on natural factors such as region, time and season, which have an impact on the distributed power generation efficiency and cost of renewable clean energy [7]. From the perspective of electricity cost, the electricity price mechanism can be divided into two parts: the capacity price proportional to the capacity, and the energy price associated with natural factors. It can reasonably reflect the power production cost structure.

The capacity price represents the fixed investment cost in the power generation cost of micro-grid users and has nothing to do with the actual electricity consumption. Due to the high cost of renewable clean energy generation, an additional incentive capacity price (f_s) is required based on the conventional capacity price. The capacity price of DG smart node is expressed as:

$$F_C = \frac{[\sum_{j=1}^{n} I_j (1+i_0)^{n-j}] A_0 (1+r)}{Q(1+\lambda)\beta} + \mathrm{f}_s \qquad (1)$$

Where n is the construction period of the DG system; I_j is the construction investment in the jth year; i_0 is the benchmark discount rate; A_0 is present value interest factors of annuity (PVIFA), r is the annual operation and maintenance rate; Q is the installed capacity; λ is the power consumption rate; β is the available rate of DG system.

The energy price represents the variable cost among users. Considering the load variation on the user side of the micro-grid, RTP at different levels is reasonably formulated based on peak-valley time-of-use price model. The Compensated energy Price linked to Power Market Transaction Cloud Platform in peak time, the flat time corresponds to the Planned energy Price, and the Selling energy Price at the valley time. The energy price is determined by the energy distribution matrix ($\boldsymbol{P_0}$), the energy index ε and the increase coefficient of other variable cost (η). The energy price of DG smart node is expressed as:

$$C_C = P_0\varepsilon_C(1+\eta)/1000 \tag{2}$$

$$C_P = P_0\varepsilon_P(1+\eta)/1000 \tag{3}$$

$$C_S = P_0\varepsilon_S(1+\eta)/1000 \tag{4}$$

Where C_C is the compensated energy price, C_P is the planned energy price, C_S is the selling energy price.

Due to the annual utilization hours of generator set (t_c, t_p, t_s) and peak load regulation capacity, the capacity fixed cost is settled into the electricity price mechanism according to a certain proportional coefficient (α) and weighting factors (K_C, K_P, K_S). RTP of DG smart node is as shown below.

$$P_C = \frac{F_C \times \alpha}{t_C} + \frac{F_C \times (1-\alpha) K_C}{t_C} + C_C \tag{5}$$

$$P_P = \frac{F_C \times \alpha}{t_P} + \frac{F_C \times (1-\alpha) K_P}{t_P} + C_P \tag{6}$$

$$P_S = \frac{F_C \times \alpha}{t_S} + \frac{F_C \times (1-\alpha) K_S}{t_S} + C_S \tag{7}$$

Where P_C is the compensated price, P_P is the planned price, P_S is the selling price.

This paper uses the method of cost accounting. Based on the cost of power generation, the mathematical model is established and the RTP is calculated according to the real-time distribution of energy. It can guarantee the economic benefits of micro-grid users through reasonable consideration of electricity and load factors. RTP can optimize the utilization of electricity resources.

IV. REALIZATION OF TRANSACTION MECHANISM BASED ON MASTER-SLAVE SMART CONTRACT

Smart contract is a logical code that relies on blockchain cloud platform. It can automatically execute contract content and cannot be changed. Smart contract ensures that trading system can accurately transfer data and assets without third-party credit guarantees. As the port of power market transaction cloud platform and the physical network topology, smart contract can realize the accurate measurement and intelligent scheduling of electricity.

A Transaction decision analysis

The randomness and intermittent nature of distributed power generation system lead to the difference between actual generation and predicted generation. In order to rebuild the micro-grid transaction mechanism, traditional power transaction objects need to upgrade to DG smart nodes. The transaction process is shown in Fig. 2. Combining the physical network topology of micro-grid with the power market transaction cloud platform, users can register online. The monitoring management system can upload all electrical parameters to the cloud platform for analysis and decision-making through the communication control function of CPS.

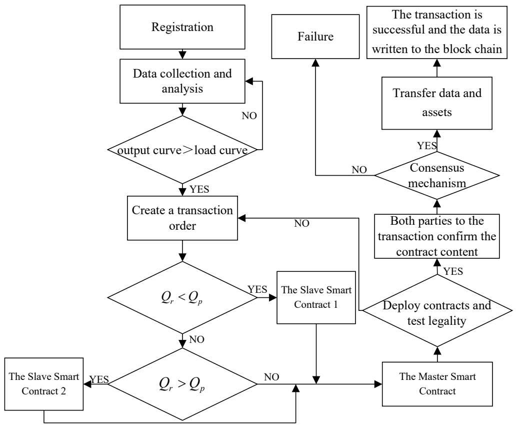

Figure 2. Transaction flow chart based on Master-Slave smart contract

Firstly, the constraints and path optimization are considered in the transaction process. The objective function is the cost of energy from generator to consumer. The function reflects the whole economic dispatch of power system with transmission element security and load priority.

$$F(x) = \min\left(\sum_{i\in S} \alpha_i \Delta P_{gi} + \sum_{i\in T} \beta_i \Delta P_{ti} + \sum_{i\in D} \gamma_i \Delta P_{li}\right) \tag{8}$$

Where S, D, and T represent power supply, transmission line, and load respectively. ΔP_{gi}, ΔP_{ti} and ΔP_{li} are the corresponding fluctuations in network power. α_i, β_i and γ_i are the cost coefficients.

The power balance condition is as follow:

$$\sum_{i\in S}^{s,t}\Delta P_{gi}=\sum_{i\in T}\Delta P_{lossi}+\sum_{i\in D}\Delta P_{li} \tag{9}$$

The power layer constraint is as follow:

$$P_{ti}+\Delta P_{li}\le P_{ti\max} \tag{10}$$

According to the economic dispatch analysis and output analysis, the system decides whether smart nodes need to create a transaction. If the output curve of distributed generation unit is higher than the internal user load curve, the power generation node (PGN) creates a transaction instruction and signs a smart contract with the power consumption node (PCN).

B Master-Slave Smart Contract transaction mechanism

The monitoring management system can extract and understand energy information. And it forms information flow to the cloud platform. Information flow and energy flow are coupled and interacted to achieve transaction behavior in the cloud platform.

When PGN and PCN reach an agreement to initiate a transaction order, the cloud platform calculates and analyzes the RTP curve to determine the current electricity price. Cloud computing intelligently detects whether the real transaction volume produced by PGN has reached the plan transaction volume. If the real transaction volume is equal to the planned transaction volume ($Q_r=Q_p$), the master smart contract is automatically executed to transfer the assets at the Planned Price and sell the planned transaction volume to PCN; If the real transaction volume is less than the planned transaction volume ($Q_r<Q_p$), the slave smart contract 1 needs to be invoked to conduct the compensation transaction with another smart node at compensated price. PGN will buy insufficient transaction volume; If the real transaction volume is more than the planned transaction volume ($Q_r>Q_p$), PGN can choose to invoke the slave smart contract 2 with PCN to sell the transaction volume at selling price.

When the smart contract is confirmed, this transaction will be broadcast in blockchain network. Each node in the network will review and confirm the information of the transaction based on the consensus mechanism. The smart contract will be strictly enforced if a majority of network nodes reach a consensus on this transaction.

C Implementation of Master-Slave Smart Contract coding

The form of the smart contract is similar to that of ordinary language, the most popular languages for writing smart contracts are Solidity.

"Address" in the contract is actually a 20-byte Ethereum address. As a global variable, "msg" can use "sender" instruction to obtain the real-time address of the current function. The relevant DG smart node structure needs to be defined, including a series of basic information required by the transaction.

```
struct Saler {
        address sale;
        uint plan_price;
        uint plan_Q;
    }
    mapping(address => Saler) public salers;
}
```

Smart contracts are mainly used to control the triggering of transactions. In power market, it is necessary to access external data in real time to complete the triggering and execution of the transaction. Oraclize, as a data transmitter, can establish a reliable connection between the cloud platform and Web APIs. Inheriting the Oraclize contract in the transaction and use the callback function to return the data. The contract automatically identifies the actual transaction quantity and RTP.

In order to implement the invocation between master smart contract and slave smart contract, the interface needs to be defined, as shown in table 1.

Table I Interfaces of Master-Slave Smart Contract

name	***instruction***
Subordinate_one	slave smart contract 1, identify the compensation price
Subordinate_two	slave smart contract 2, identify the selling price

Triggering a transaction must satisfy the following constrains:

Function payment_a(address sale, uint actual){
If(

$$F(x)=\min\left(\sum_{i\in S}\alpha_i\Delta P_{gi}+\sum_{i\in T}\beta_i\Delta P_{ti}+\sum_{i\in D}\gamma_i\Delta P_{li}\right)$$

$$\sum_{i\in S}^{s,t}\Delta P_{gi}=\sum_{i\in T}\Delta P_{lossi}+\sum_{i\in D}\Delta P_{li}$$

$$P_{ti}+\Delta P_{li}\le P_{ti\max}$$),

{Send(purchase, sale,value); }}

V. ACTUAL CASE CALCULATION

Taking the actual data as an example, DG smart node A can trade with DG smart node B through data analysis of the monitoring management system. Where A is a photovoltaic power generation user, and B is a power consumption factory. The data on the user side is shown in the following table.

Table II Relevant parameters of user A

smart node	*W_G/MW*	*A_0*	*I_f/RMB*
A	100	6.002	5000

Table III K value in different periods

	Peak	*Flat*	*Valley*
K	0.438	0.328	0.234

According to the statistics of sunshine duration in a certain area of China, The average energy distribution matrix of sunny days P_{o_sun}= [0 0 0 20 100 150 400 200 800 600 700 800 810 500 430 530 550 450 300 150 10 0 0 0], clearness index ε_{sun}=70%. The average energy distribution matrix of cloudy days P_{o_cloudy}= [0 0 0 0 50 100 200 410 400 600 700 800 610 600 400 500 420 290 180 70 30 0 0 0], clearness index ε_{cloudy}=50%. The average energy distribution matrix of rainy days P_{o_rainy}= [0 0 0 0 5 50 100 300 250 200 400 420 600 650 500 530 210 140 50 3 0 0 0 0], clearness index ε_{rainy}=20%. Annual use of generating sets for 2000 hours .Other parameter values are shown in table 4.

Table IV parameter list

name	**value**	**name**	**value**
r	3%	**i_0**	12%
λ	4%	**η**	10%
β	80%	**α**	0.475

The daily real-time electricity price curve can be obtained based on Matlab simulation as shown in Fig. 3. The blue curve is the peak section RTP, the red curve is the flat section RTP, and the green curve is the valley section RTP.

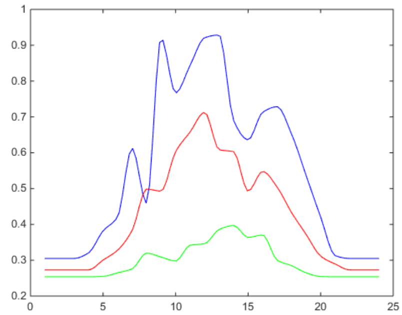

Figure 3. Daily real-time electricity price curve

The smart contract identifies the average value of the RTP, as shown in Table 5.

Table V The real-time price

Compensation price	*Planned Price*	*Selling price*
0.5359	0.4379	0.3297

A and B reached a trading volume of 10KWh and signed Master-Slave smart contract.

In this example, the contract code is written in Solidity, and the Remix online compiler is simulated as shown in Fig .4. However, the output of A may fluctuate uncontrollably at any time due to changes in the weather during the course of transaction. Transaction failure caused by intermittency and randomness of micro-grid generation can be effectively solved by deploying Master-Slave smart contracts.

Figure 4. Master-Slave smart contract Simulation

VI. CONCLUSION

This paper combines physical topology, Internet communication technology, cloud computing technology, and blockchain bottom technology. The physical network topology realizes the real-time monitoring and analysis of the electrical quantities. The power market transaction cloud platform can intelligently analyze the distribution and price curve of power resources. It assists smart nodes to reach an agreement to complete transactions based on Master-Slave smart contracts. The data generated by the transaction process is written to the blockchain, and can't be changed. Transaction Mechanism based on Master-Slave contract ensures the fairness and reliability of the transaction.

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