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Combined game model and investment decision making of power grid-distributed energy system

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Abstract
Distributed energy based on clean energy has gradually become a progressively important part of the energy system due to increasingly prominent environmental problems and energy crises. Presently, the development of distributed energy has the phenomena of investment chaos, resource waste, and information asymmetry. We propose a grid-distributed energy system joint decision-making model based on the alliance blockchain to solve problems including the power generation strategy of distributed energy users and the grid investment plan connected to the distributed system. Firstly, we construct the return models of the distributed energy system and the power grid system separately. Secondly, combined with the analysis of the game mechanism of different entities, we propose a multi-agent decision-making model of the distributed energy system based on the alliance blockchain. Thirdly, based on this model, we optimize the revenue of the entire system through the dynamic game and use the alliance chain and smart contract to automatically execute. Finally, the model is solved by the iterative search method, and the entire simulation process is implemented in Ethereum using python. Based on the idea of joint decision making, our study considers the interests of all participants, ensures that the participants maximize their benefits in the game process, optimizes the investment decisions of each entity, and improves the effectiveness of the grid-distributed energy system decision making.

Keywords Grid company · Distributed energy · Blockchain · Dynamic game

1 Introduction

With the increasing development of environmental issues and energy crises, the distributed energy system governed by clean energy has become a more and more important part of the energy system gradually. At present, the development of distributed energy systems

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has such disadvantages as disorder investment, wasted resources, as well as asymmetric information. According to the provisions in *Regulations of Full Guarantee Acquisition for Renewable Energy Generation* (National Energy Administration., 2016), there is no region where renewable energy generation is limited, and power grid enterprises should guarantee the grid-connected project of the renewable energy generation, purchasing all the generated energy. Generally, distributed energy generation is combined to the grid or included into the power-purchasing plan ahead of time in the manner of contract presently. But distributed energy system is characterized by disabling power generation, which results in the possible difference between the generation plan and actual power generation, as well as an increase in difficulty of power grid dispatching; and the distributed energy system is asymmetric with the power grid in the information, which causes waste investment in the power grid. The thesis puts forward the combined decision-making model of power grid-distributed energy systems based on the consortium blockchain, the decision-making issues include generating strategies of distributed energy users; furthermore, the thesis studies the plan of power grid investment linking with the distributed system. The investment in various subjects is optimized from the angle of combined decision making of power grid-distributed energy systems based on the blockchain technology and game theory in this research. The trading platform is established with blockchain to ensure the automatic and standard running of the trade. Interest demands for different subjects are independent of each other, their decision makings are carried out based on individual rationality and are balanced in the process of the game.

Presently, there is rare literature about the research on the combination of the power grid and distributed energy system, not to speak of the literature about the research on the combination of blockchain technology and game theory. In the thesis, a combined decision-making model of power grid-distributed energy system is put forward, and the model considering a combined game when many subjects make decisions are executed automatically based on a consortium blockchain. Firstly the return model of distributed energy system and the relative power grid companies is established; Secondly, a dynamic game model related to combined decision making of power grid-distributed energy system is put forward based on analysis on the game mechanism, and a mixed trend model based on sequence solving method is put forward to conduct the safety correction on many decision-making schemes; finally, the model is solved by iterative search method. The game relations among different subjects are fully considered based on the thinking of the combined decision making in the thesis so that the economic safety and reliability for decision making are ensured from the integrated angle of the power grid-distributed energy system. What's more, the maximization of earnings for the participants in the process of the game is guaranteed to improve the effectiveness of decision making of power grid-distributed energy systems. Finally, the rationality and effectiveness of the model are verified in the thesis based on the simulation results of the typical cases.

There are three main contributions of this study. Firstly, based on the dynamic game theory, a joint decision model for power grid and distributed energy system is established, to maximize the value of the objective function to achieve the maximum economic benefits and social welfare of each agent, which optimizes system resource allocation and increases the penetration rate of distributed energy. A typical power system is taken as a case to simulate and solve the Nash bargaining to illustrate the feasibility of the constructed model. Secondly, the integrated application of blockchain technology plays an important role in the field of business process reconstruction and industrial interaction model innovation. This research introduces blockchain technology to design an investment decision-making system based on the alliance chain. Meanwhile, the smart contracts are deployed on the blockchain to automatically execute power grid-distributed energy system transactions. It's a preliminary exploration for the development of distributed energy transactions. Thirdly, from the perspective of each investment agent, this paper uses multi-agent technology to analyze the game transfer relationship between the main agents, and further studies the dynamic game decision-making behaviors, which meets the interests of different agents, which also enhances the economy and reliability of investment in power grid companies and distributed energy systems.

The structure of the remainder is as follows. Section 2 presents a brief review of the literature about the application of blockchain technology in the distributed energy system and game theory in the decision model. Section 3 elaborates the dynamic game method used in this paper and the game behaviors of each agent, which also provides Nash equilibrium strategy. In Sect. 4, a typical case is simulated; the results and discussion under different investment strategy scenarios are obtained. Based on the above research, the main conclusions of this paper are drawn in Sect. 5.

2 Literature review

Blockchain is a series of lists related to the data blocks, the trading data can be stored in the distributed system with de-trust, traceability, and un-modification. The blockchain is characterized by decentralization and automation of contract execution. In blockchain technologies, consortium blockchain which is similar to distributed database technology is more suitable for the scene with more trading nodes, more trade quantity, and higher trading frequency (Tai et al., 2017; Wang & Liu, 2019), and more suitable for being applied to the distributed energy system. Wu and Tran (2018) discussed the application of blockchain in the sustainable energy system and analyzed the challenges existing in the application of it to the energy Internet. Ahl et al. (2019) established the peer-to-peer (P2P) microgrids analysis frame for blockchain based on a general survey of peer-to-peer (P2P) microgrids and put forward the actual significance of the frame on the development of distributed energy institutions. Hou et al. (2020) analyzed the competitiveness of the distributed energy by using Michael Porter's five competitive models, and analyzed the combined development mode of "blockchain technology + distributed energy" by using the SWOT model, and concluded that blockchain technology can enhance the competitiveness of distributed energy. In the literature (Ding, 2015; Lu et al., 2017), settlement smart contract of electric market trade was designed, the key technical difficulties were analyzed, and provided the solutions. Li et al., (2019) put forward a hierarchical structure frame of energy demand-side management which is realized by P2P exchange of energy in the real-time market, so as to realize the safety and efficiency of multi-sectoral demands and distributed energy system management of renewable energy generation by utilizing smart contract and blockchain scheme. In the literature (Jin et al., 2019), the charging and trading model of electro mobiles based on consortium blockchains, and the feasibility of the above methods was verified by taking the actual distribution scene of the charging stations in the region of Tianjin City as the example. In the literature (Xie et al., 2019; Zheng, 2019), the model of microgrid economic dispatching based on blockchain was studied, the decentralization economic dispatching was realized by blockchain. In the literature (She et al., 2019), a kind of model of multi-energy complementary safe trading based on isomeric energy blockchain was put forward to solve the issues related to multi-energy complementation and integrated trading of distributed energy in energy trading systems. The combined decision-making model of power grid-distributed energy system based on the consortium chain can be automatically executed while various subjects' privacy is kept.

Nowadays, the application of blockchain technology in distributed energy trading can be divided into three categories: transaction process design, consensus mechanism design, and system optimization design. The research on transaction process design can be divided into four aspects. Firstly, there is some research about the market transaction model. Wang et al., (2018) proposed a parallel bidding framework based on the three-layer distribution network architecture and the decentralized characteristics of the blockchain to support energy transactions between microgrids. Wei et al., (2021) constructed a distributed energy peer-to-peer trading framework based on blockchain, using technologies such as credit value evaluation, intelligent contracts, and energy currency incentive mechanisms to support fast and frequent energy transactions and overcome the confirmation delay of energy blockchain transactions. Luo et al., (2019) proposed a distributed power trading system for producers in the active distribution network (ADN), which uses technologies such as multi-agent system, agent alliance mechanism, and blockchain transaction settlement mechanism to solve the problem of determining energy transaction prices separately and promote peer-to-peer power-sharing among producers. Okoye et al., (2020) proposed a network-enhanced transaction microgrid model that uses blockchain technology and optimized participant license agreements to improve transaction speed and convenience. Secondly, there is research about auction mechanisms. Zhao et al., (2020) proposed a two-layer framework of energy transaction between the multi-layer microgrid and internal microgrid based on blockchain and adopted a transaction method of continuous double auction mechanism to effectively reduce the transaction volume with the main grid and improve energy efficiency. Wang Jianmin et al. proposed a decentralized power trading system for microgrids based on blockchain and a continuous double auction (CDA) mechanism. The system can quickly achieve market balance and is suitable for short-term microgrid trading. It promotes the development of an integrated energy trading protocol based on blockchain and the engineering application of integrated energy trading (Wang et al., 2017; Zhao et al., 2018).

Thirdly, there is research about demand response management. Noor et al., (2018) introduced a distributed energy management model based on blockchain, including energy supply control, storage management, and game theory algorithms, to achieve decentralized demand-side management and promote peer-to-peer transactions according to the optimized demand profile. Claudia et al., (2018) proposed a distributed control model of medium / low voltage smart grid based on blockchain by establishing and running decentralized peer-to-peer energy flexibility. It is found that distributed DSM based on the blockchain can be used to match energy demand and production at the smart grid level, improve the tracking accuracy of demand response signals, and reduce the energy flexibility required for convergence. Afzal et al., (2020) proposed a distributed demand-side management system based on blockchain technology among multiple households in the community microgrid. The equipment of a single household in the intelligence community is scheduled through electricity price so that the generated renewable energy is consumed locally in the community microgrid, while the transaction is carried out on the blockchain without the need for a central control entity, to achieve the purpose of reducing energy consumption. Wu et al., (2017) proposed a demand-side response resource point-to-point transaction framework based on blockchain technology and energy management system EMS to realize dynamic real-time scheduling of energy transactions. Fourthly, there is research about security and privacy. Gai et al., (2019) proposed a transaction model using federated blockchain in a smart grid. This model proposes a privacy protection method based on noise to hide the transaction distribution trend of adjacent energy trading systems supported by blockchain to protect the problem of privacy leakage in energy transactions. She et al., (2018) proposed a kind of distributed energy transaction authentication model based on an alliance chain. The model protects the private data of all parties to a certain extent through blockchain rights proof, data encryption, timestamp, distributed consensus, and data separation. Guan et al., (2021) proposed a distributed energy transaction scheme based on privacy protection based on blockchain. by introducing the encryption algorithm based on ciphertext policy (CP-ABE) as the core algorithm to reconstruct the transaction model, this algorithm realizes fine-grained access control through transaction arbitration in the form of ciphertext. This design greatly improves the security and reliability of the transaction model.

Game theory has been applied widely in the aspects of generation decision making related to the power system, grid structure decision, etc. (Chen, et al., 2017; Contreras & Wu, 2000; Lu et al., 2014; Ng et al., 2009). Saeed et al., (2017) studied the market prices of suppliers and consumers in the uncontrolled retail electricity market based on game theory and Nash equilibrium theory, putting forward a highly dynamic electricity market frame, and as a result, the effectiveness of the frame was verified. Mei et al., (2012) discussed the cooperative game problem of stroke, light, and storage in a hybrid power system, and proposed, analyzed, and compared four typical distribution strategies. Based on the dynamic game theory of complete information, Jin et al., (2017) built a decision model for photovoltaic, energy storage, and power grid, which could realize rational optical storage layout and coordinated decision of power grid while ensuring the maximum benefit of participants. Based on the analysis of the game mechanism of different investment entities, Yang et al., (2019) proposed a dynamic game model for joint decision making of power-natural gas integrated energy system, and the simulation results verified the effectiveness and rationality of the model. Lu, (2017) proposed a cooperative evolution model considering node altruism, and introduced the evolutionary game theory, which shows that individual altruism can effectively promote cooperation in the cooperative evolution model considering individual altruism.

With the wide application of game theory in power systems, the combination of game theory and blockchain technology has gradually become a new trend of distributed energy development. Gong et al., (2021) have constructed a co-governance trading environment between aggregators and multiple microgrid trading agents in microgrid groups and a new energy trading model between aggregators and microgrid nodes based on blockchain technology. The blockchain aggregator–microgrid group alliance transaction architecture, block data structure, environmental identification factor incentive mechanism of dynamic cooperative game, and intelligent contract supported by the multi-objective evolutionary algorithm are designed. The co-governance coefficient is proposed to evaluate the effectiveness of the microgrid group operation strategy, which shows that the co-governance transaction model can effectively promote the local consumption of renewable energy, improve the energy supply structure of microgrid nodes, and promote the low-carbon sustainable development of microgrid groups. She et al., (2019) constructed a multi-energy complementary security transaction model MCST-HEB of heterogeneous energy blockchain. By constructing the energy index transaction relay chain and the energy supply parallel chain, the model realizes the integration of a variety of distributed energy uplinks into the grid and can carry out multi-energy complementary and integrated scheduling of various kinds of distributed energy connected to the grid, so that the transaction of multiple energy can be carried out directly between the energy supplier and the energy consumer.

Considering the role of game theory in joint decision making, Wang et al., (2018) proposed the construction and simulation of a single-agent new energy seller decision-making model in spot market based on stochastic–robust hybrid optimization method, construction, and simulation of a single-agent buyer decision model in spot market based on stochastic integer mixed optimization method, construction, and simulation of spot market multi-agent decision model based on GDCAC algorithm, improvement of spot market-clearing model and construction and simulation of multi-agent decision-making model under new energy bidding based on robust optimization and LSCAC algorithm. On the one hand, the multi-agent decision-making model can provide quantitative decision-making tools for "price influencers" participants to trade in the spot electricity market. On the other hand, it can provide quantitative analysis tools and simulation platforms for market economy operation simulation, market planning, and design, policy effect estimation, and other related research.

For the application of complete-information game theory in decision making, Jenabi et al., (2013) put forward an extended decision-making model considering power generation companies and transmission companies. The results show that joint decision making of generation and transmission can fully tap the transmission capacity of the power grid and effectively alleviate transmission congestion, and achieve win–win results for both generation and transmission. The extended decision-making model related to power generating companies and transmission companies was built based on complete-information game theory, and the result showed that the combined decision making of power generating and transmission can explore the transmission capacity of the power grid and relieve transmission block effectively to realize a win–win of power generating party and transmission party. Yu et al., (2017) put forward a kind of new DR (demand response) resource trading frame based on incentive mechanism, analyzed the interaction among the different participants in the electricity market by using two-loop Stackelberg game, proving that the method can compensate for the lack of resource with the minimized cost. Furthermore, Wang et al., (2020) put forward a kind of comprehensive risk evaluation method of the independent power system operator (ESO) and independent heat supply system operator (HSO) and established The post-contingency dispatch model for The integrated electricity and heat system (IEHS) based on Stackelberg game model, and the result proved that the method can coordinate the after-emergency dispatching of energy operator effectively, reducing the anticipated cost. Liang et al., (2017) put forward a kind of smart grid-distributed demand-side energy management plan based on an ordered state based on game theory, minimizing the gross of energy procurement of total power cost, supply capacity of power-distribution infrastructure, individual appliance, and users' energy demand target by using distribution algorithm. Li and Yan, (2020) put forward a kind of real-time pricing (RTP) scheme balancing real-time demand and transferring peak demand based on the non-cooperative game, analyzing the best strategy associated with energy consumption, power generating, and storage power arranged for users, in the meantime, the privacy of users and power suppliers were protected, and the effectiveness of the scheme was verified by the simulation result. There is a rarely combined application of game theory and blockchain. Amin et al., (2020) put forward a kind of P2P electricity transaction frame of incorporating both non-cooperative and cooperative games to ensure the stability of contract between prosumers and consumers, realizing win–win.

3 Methods

3.1 Return model of participants in power grid-distributed energy system

The typical participants in the power grid-distributed energy system include distributed energy system and its linked power grid. See Fig. 1.

A distributed energy system can generate power to be included in the grid, and purchase power from the grid. The model only considers the game between power generation to be included in the grid and investment in the power grid for distributed energy. The distributed energy system hopes to improve the investment benefits of its power generating facilities to reduce running costs. Furthermore, the distributed energy is governed by renewable clean energy which will result in environmental benefits. Power grid companies hope to improve investment benefits in the power grid. Different subjects which are independent of each other have different targets when making a decision. In the thesis, the difference between the total income of the grid and the total cost of the grid was calculated to obtain the benefits by combining with dynamic game theory, grid safety constraint is considered, and the returned model for different participants is established.

3.1.1 Return model of the distributed energy system

The total revenue of the distributed energy system contains enterprise economic benefits and social benefits. The enterprise economic benefits in this model mainly refer to revenue from selling electricity, and the social benefits mainly refer to environmental benefits. See the following formula (1):

$$F_F = F_{\mathrm{GSE}} + I_{\mathrm{GEC}} \tag{1}$$

where F_{F} denotes the total revenue function of distributed energy systems within the life cycle, FGSE denotes the on-grid revenue of distributed energy, IGEC denotes social benefits. But time value of capital is not considered in the model.

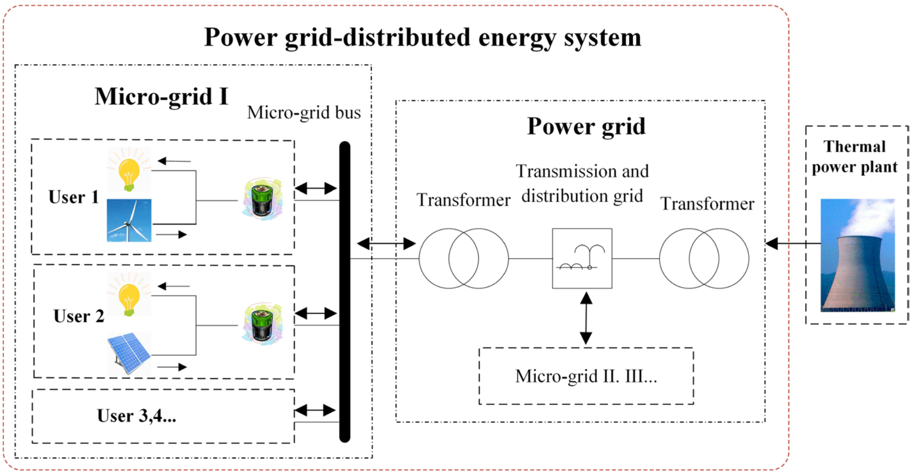

Fig. 1 Typical power grid-distributed energy system

The on-grid revenue refers to the difference between the on-grid income and the cost, as shown in formula (2):

$$F_{\mathrm{GSE}} = I_{\mathrm{GSE}} - C_{\mathrm{IG}} - C_{\mathrm{GO}}. \tag{2}$$

I_{GSE} denotes the on-grid income of distributed energy within the life cycle, CIG denotes the investment cost of distributed power generating equipment, and CGO denotes the running cost.

The social benefits I_{GSE} is shown in formula (3):

$$I_{\mathrm{GSE}} = \sum_{t=1}^{T} E_{Bdt} \times \rho_s. \tag{3}$$

t refers to life cycle-level year; T refers to total life cycle; $E_{\mathrm{Bd}t}$ refers to power sale quantity of t level year; ρ_s refers to the average on-grid price.

Because of different service life cycles of different equipment, the costs are shared equally within the life cycle, as shown in formula (4):

$$C_{\mathrm{IG}} = \frac{1}{T_G} \sum_{i=1}^{S_{\mathrm{GGU}}} X_i \alpha_i. \tag{4}$$

S_{GGU} denotes the set to be selected for distributed power generating equipment, x_i denotes the 0–1 variable of investment for distributed power generating equipment i; α_i denotes the investment fee for distributed power generating equipment i; T_{G} denotes the service life of distributed power generating equipment.

$$C_{\mathrm{GO}} = \sum_{i=1}^{T} g_{\mathrm{ut}} \left(C_{\mathrm{GCu}} \right) P_{\mathrm{GU}}. \tag{5}$$

In formula (5), u denotes the number of distributed powers generating equipment; g_{ut} denotes the running time of distributed power generating equipment u at t level year; $C_{\mathrm{GC}u}$ denotes the running cost of distributed power generating equipment u at the unit power; $P_{\mathrm{G}u}$ denotes the active power of distributed power generating equipment u.

$$I_{\mathrm{GEC}} = \sum_{i=1}^{T} g_{\mathrm{ut}} \left(C_{\mathrm{CCu}} \right) P_{\mathrm{GU}}. \tag{6}$$

The environmental benefits of the distributed system are weighed by the environmental cost of the traditional coal-fired unit. In formula (6), $C_{\mathrm{CC}u}$ denotes the environmental cost of the traditional coal-fired unit u at the unit power.

3.1.2 Investment income model of grid company

The income of grid company includes the difference between on-grid price and selling power price of the distributed energy system, the cost mainly contains net rack investment cost. The calculation is shown in formula (7):

$$F_E = I_{\mathrm{ESE}} - I_{\mathrm{GSE}} - C_{\mathrm{IT}} - C_{\mathrm{TL}}. \tag{7}$$

F_{E} denotes the revenue of grid company in the power grid-distributed energy system, I_{ESE} $-I_{\mathrm{GSE}}$ denotes the difference between selling power price and on-grid price, C_{IT} denotes the net rack investment cost, and C_{TL} denotes power loss cost.

$$I_{\mathrm{ESE}} = \sum_{t=1}^{T} E_{Ldt} \times \rho_E. \tag{8}$$

In formula (8), $E_{\mathrm{Ld}t}$ denotes the annual load at t level year; ρ_E denotes the mean selling power price of a grid company within the life cycle.

$$C_{\mathrm{IT}} = \frac{1}{T_{\mathrm{TL}}} \sum_{i=1}^{S_{\mathrm{TL}}} y_i \beta_j. \tag{9}$$

In formula (9), S_{TL} denotes the set to be selected for the power grid investment project; y_j denotes the investment 0–1 variable of the item j; β_j denotes the investment fee of the item j; T_{TL} denotes the service life of the capital.

$$C_{\mathrm{GO}} = \sum_{t=1}^{T} N_{\mathrm{LOSSlt}}\left(\mu_i\right). \tag{10}$$

In formula (10), l refers to the item number; $N_{\mathrm{LOSS}lt}$ refers to the power loss of line 1 supporting the item at t level year; μ_l refers to the power loss fee for the unit line.

Constraint conditions include:

- Power grid constraint:

In the power system grid, the injection currents for all the nodes are balanced with the output currents, as shown in formula (11):

$$\sum_{l \in S_1} H_{\eta l} f_{\mathrm{Llt}} + \sum_{m \in S_2} J_{\eta m} P_{\mathrm{gmt}} - \sum_{k \in S_3} K_{\eta k} E_{\mathrm{Ld}kt} = 0; \forall \eta \in S_4, \forall t. \tag{11}$$

H denotes the incidence matrix of power lines with nodes in the power grid, J denotes the incidence matrix of generator with nodes in the power grid and K denotes the incidence matrix of load with nodes in the power grid; $f_{\mathrm{L}lt}$ denotes the currents on the line l at t level year; P_{gmt} denotes the output of the generator m at t level year; $E_{\mathrm{Ld}kt}$ denotes the load on the node k at t level year; S_1 denotes the power line set, S_2 denotes the generator set, S_3 denotes the power load set, S_4 denotes the node-set of the power grid.

- Current constraint:

The current balance constraint formula is established by the Newton–Raphson formula (Lu et al., 2014), as shown in formula (12)

$$\begin{cases} P_q = U_q \sum_{q \in r} U_r (G_{\mathrm{qr}} \cos \theta_{\mathrm{qr}} + B_{\mathrm{qr}} \sin \theta_{\mathrm{qr}}) \\ Q_q = U_q \sum_{q \in r} U_r \left(G_{\mathrm{qr}} \sin \theta_{\mathrm{qr}} - B_{\mathrm{qr}} \cos \theta_{\mathrm{qr}}\right) \end{cases}. \tag{12}$$

P_q and Q_q denote the active injection power and reactive injection power at the node q, respectively; U_q and U_r denote the voltage amplitude of the node q and r, respectively; G_{qr} and B_{qr} denote the electric conductance and electrical susceptance of the branch q_r, respectively; θ_{qr} denotes the voltage phase angle difference between the node q and r.

- Transmission capacity constraint of lines

$$-f_{\mathrm{Lqr}}^{\max} \leq f_{\mathrm{Lqr}} \leq f_{\mathrm{Lqr}}^{\max}. \tag{13}$$

In formula (13), f_{Lqr} denotes the current of the line qr; $f_{\mathrm{Lqr}}^{\max}$ denotes the maximum capacity permitted for transmission of the line qr.

3.2 Combined decision-making model of power grid-distributed energy system based on a consortium blockchain

The requirements for processing information in the combined decision-making model of power grid-distributed energy system mainly include information safety for trading; protection of privacy of participants; protection of the important assets and commercially confidential information; prevention from fabrication and modification of trading data; improvement of transparency and reliability of settlement of trading and insurance real-time data. The alliance chain is introduced to construct the joint decision-making model of power grid-distributed energy system, and the alliance chain records information, including power supply plan and user information of distributed energy system, user purchase plan, investment information of power grid company, energy information, and transaction information. Smart contracts consist of three sub-contracts, namely, the matching contract, the credit mechanism contract, and the payment contract. Each subject uploads the supply and demand requirements, plans, and so on to the chain. After the intelligent contract is loaded with the algorithm, the buyers and sellers on the chain carry out point-to-point matching and match the buying and selling transactions. The transaction results affect the decision-making investment among the subjects, and then continue to affect the market trading results. To pursue the maximum income, each subject continues to adjust investment decisions, so repeatedly, the formation of a game, as shown in Fig. 2. Among them, the game process includes game relationship transmission, game decision making, mixed power flow, and game solution. Smart contracts are simply understood as the terms of the digital version and the agreements required to enforce them. Smart contracts are deployed on the blockchain and are executed automatically as part of transaction validation. After the contract is created, the contract will be represented as a special identity string, and the smart contract consists of the contract address, the contract account balance, a predefined executable code, and several status variables. Different users interact with the intelligent contract by sending the transaction of the calling contract to the known contract address.

The decision-making target is to optimize the equilibrium state of the power grid-distributed energy system in the process of the dynamic game through the interaction of game relationships among the subjects. The overall model related to the combined decision making of power grid-distributed energy systems based on consortium blockchain is shown in Fig. 2. In Figs. 2.1–2.4, the model is analyzed specifically. In Fig. 2.1, distributed energy system and transfer of game relations of power grid company are described; In Fig. 2.2, dynamic game decision-making behavior is described; In Fig. 2.3, mixed currents in the game process is described; In Fig. 2.4, the model is solved by sequence solving method.

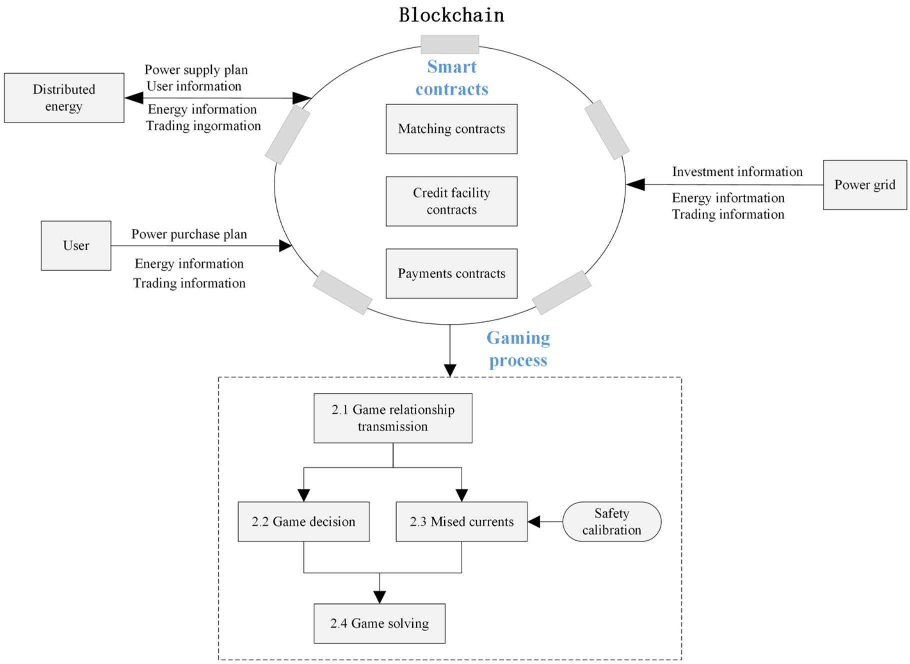

Fig. 2 The overall model related to combined decision making of power grid-distributed energy system based on a consortium blockchain

3.2.1 Game relationship transfer

Through mixed current model, distributed energy system and grid company influence mutually in the process of safety correction. In the decision process, distributed energy systems can make decisions in the aspects of investment of its power generating equipment, power utilization plan, and on-grid scheme, to influence the investment decision making of grid company. Grid companies can decide the aspect of the net rack construction investment plan to optimize investment. Grid companies and users can influence the network topology structure through current information transferred by coupling nodes. The subjects make the decision independently while influence mutually to form a game relationship. The game relationship transfer is shown in Fig. 3, in which the set to be selected for distributed power investment includes a decision to be selected for distributed generator unit within the whole life cycle; on-grid scheme and power utilization plan refer to scheme and plan for each time interval. The model is realized in blockchain, and an on-grid scheme and power utilization plan can be adjusted automatically. Net rack construction investment covers major distribution network construction plans within the whole life cycle.

3.2.2 Dynamic game decision-making behavior

The distributed system is considered as a whole in the model, without consideration of the game among various users inside the distributed system. In the process of the game,

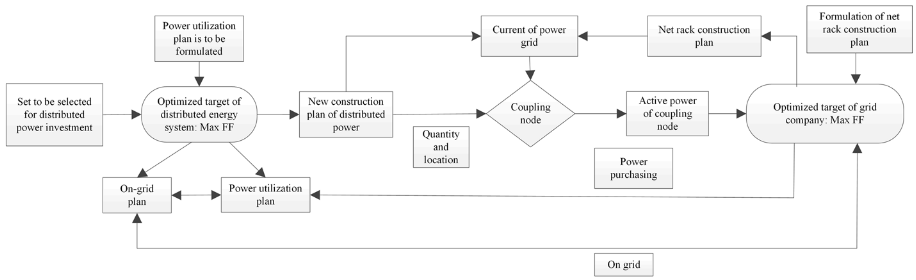

Fig. 3 Game relationship transfer

the initial electricity generation strategy is given firstly by the distributed system, then a decision-making plan is given by the grid company, which on the contrary influences strategy of distributed system. Dynamic game pattern is formed between grid company and distributed system. The game behavior is automatically completed in blockchain and smart contracts, as shown in Fig. 4.

As shown in Fig. 4, in the first game round, the distributed system decides the initial power generating plan according to its situation firstly, providing decision M_F^0, to store into the blockchain, and transfer information to grid company. While grid company provides M_E^0 by adjusting the net rack construction investment plan, calculating grid currents, then transfer current information to coupling nodes which convert current information to feedback to the distributed system, and step into the next game round after topology is updated. The game reaches Nash equilibrium state when distributed system and grid company fail to gain more returns even if a strategy is changed in the process of the game, as shown in the following formula:

$$\begin{cases} M_F^* = \arg\max F_F\left(M_E^*, M_F\right) \\ M_E^* = \arg\max F_E\left(M_E, M_F^*\right) \end{cases}. \tag{14}$$

In formula 14, M_F^* and M_E^* refer to the optimized strategy of one party, when the other party selects the optimized strategy. Both distributed systems and grid companies can gain the equilibrium maximum return by such a kind of strategy profile. Argmax () refers to the variable set when the targeted function has the maximum value. The game process is executed in the smart contract automatically.

3.2.3 Mixed currents in the process of game

In the process of the game, decision-making plans influence each other through the transfer and conversion of current parameters indirectly in the process of mixed current calculation. The specific process of safety correction for mixed currents is as follows:

(1) After the decision-making plan is confirmed by distributed energy system and grid company, the current of the power system of the net rack structure is calculated, and the plan is corrected. The current information is transferred to coupling nodes after correction;
(2) The power equilibrium relationship of coupling nodes is utilized to calculate the energy flux of coupling nodes substituted into the current model for calculation, which can realize the safety correction of decision-making plan;

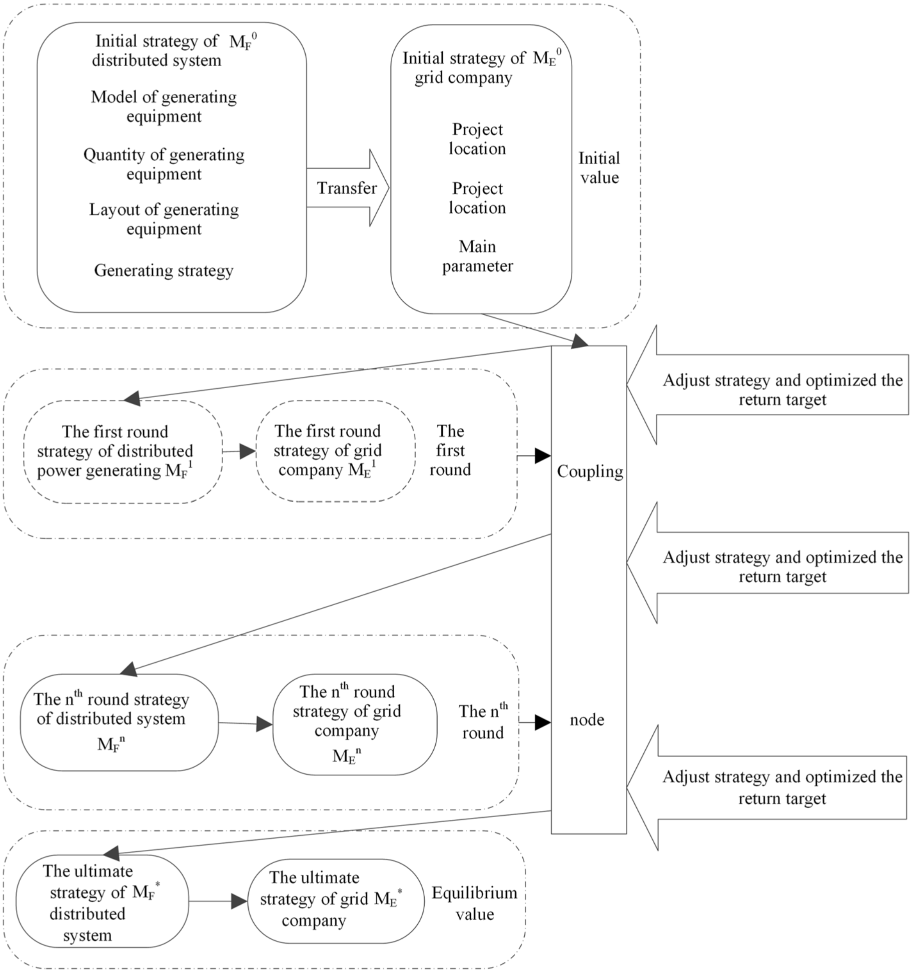

Fig. 4 Game decision-making behavior

(3) The final decision-making plan for the game round is confirmed according to the corrected result.

3.2.4 Model solving

Nash equilibrium is solved by the iterative search method in the thesis. The solving steps are as follows, and the solving flow is shown in Fig. 5.

Step 1: Input original data and parameters and initialize the data required for establishing game model, which includes user load information, parameters of generating equipment to be selected, power price, cost of distributed generating equipment, the investment cost of net rack structure for the power grid, topological parameters of the original network and other necessary parameters.

Step 2: Generate a strategy set of game participants. The distributed system generates power generating plan set $\{M_F^1, M_F^2, \ldots, M_F^{nF}\}$ according to set of generating equipment

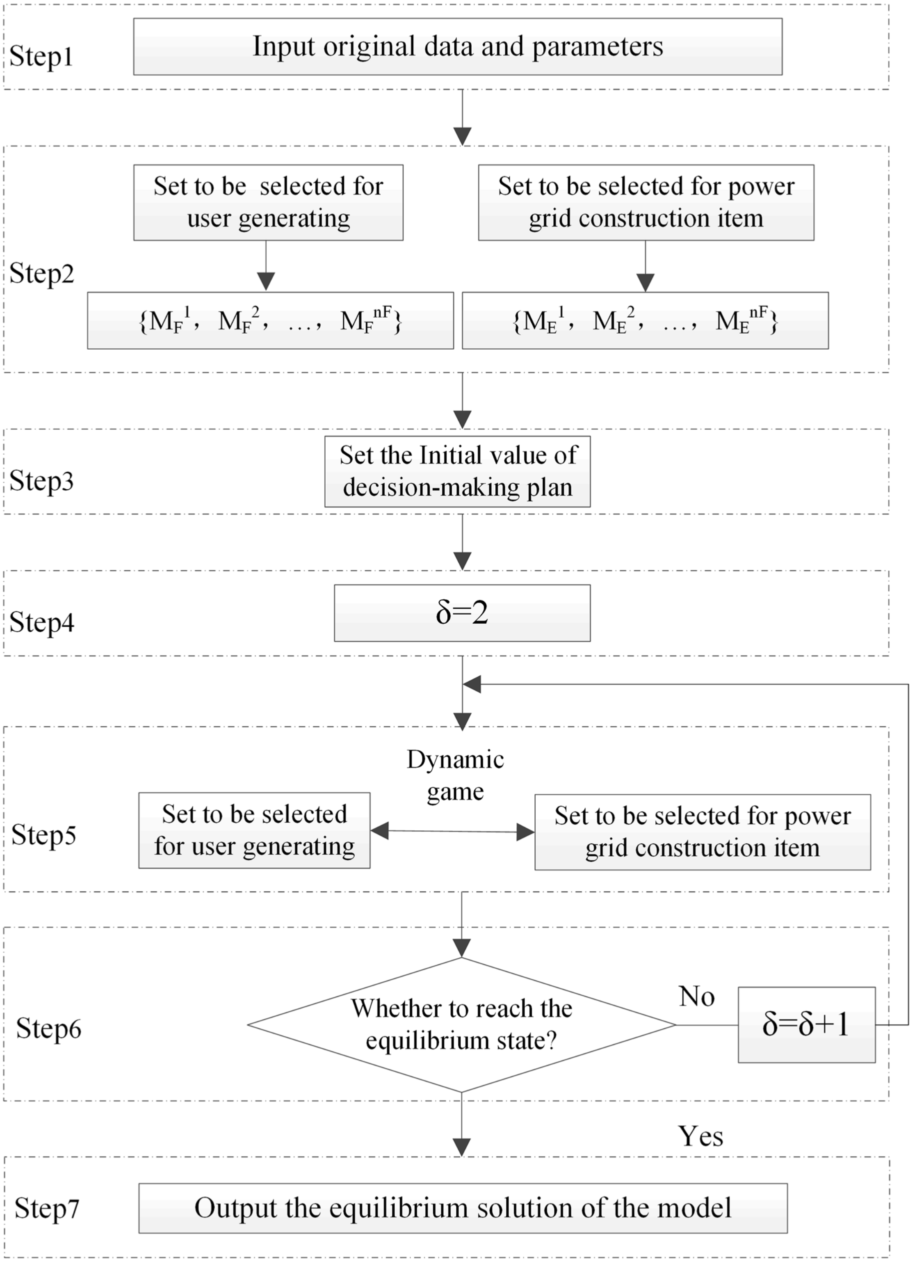

Fig. 5 The flowchart of game solving

to be selected; Grid company generates strategy set $\{M_E^1, M_E^2, \ldots, M_E^{nE}\}$ of net rack project for power grid according to set of power purchase to be selected for the distributed system. nF and nE are the totals of elements in the strategy set for distributed systems and grid company, respectively.

Step 3: Extract any group of plans as the initial value of the decision-making plan from the strategy set.

Step 4: Set the initial iterative value $\delta = 2$.

Step 5: Optimize the plan. According to the information of the last round, distributed system and grid company make the decision, correction, and calculation once again. The final return of the game round is obtained through mixed current calculation.

Step 6: Judge whether the equilibrium state is reached. If the returns of the successive two times of game rounds are the same, it will be regarded as an equilibrium state, and go to step 6; if not, $\delta = \delta + 1$, and return to step 5.

Step 7: Output the equilibrium solution (M_F^* and M_E^*) and final returns of various parties.

4 Results and discussion

4.1 Data sources

In the section, the model above mentioned is performed with the analog simulation through a typical case. The blockchain and smart contract are developed based on the Ethereum platform, and the smart contract is compiled and deployed by using python3.7 (python database). Ethereum platform is a general virtual currency platform, which can use the tools of Ethernet Square to generate an intelligent contract system for any number of different virtual currencies. As long as there is a key system that enables transactions to be tracked and parties in the platform can interact directly without any trusted third party, this untrusted intelligent contract infrastructure provides faster and cheaper transactions. Ethernet can be public or private without any permission, while the fabric is a private and licensed network. On the other hand, our project focuses on exploring the game situation among the subjects in the power market, rather than the implementation of the trading market, simplifies the construction of the platform without considering authority and confidentiality, and focuses on simulating the free trading of the electricity market. It is more convenient to build the platform in Ethernet Square.

The power grid-distributed energy system is composed of the power system of the modified IEEE24 node. The distributed energy system covers 3 sets of existing generating equipment, 5 sets of generating equipment to be selected. IEEE24 node system covers 9 generating equipment, 8 power lines to be selected, with 1 maximum expanded line for each line. Only construction of power lines is considered in the power grid investment, without considering the construction of transformer substation and power-distribution network. In this paper, photovoltaic panels with an installed capacity of 280 W and small wind turbines with 500 W are selected. The installed capacity of node 1 is 167.2 MW, which is composed of 35 distributed power points, in which each distributed PowerPoint contains 500 distributed power users whose installed capacity is less than 10 kW, and 100 distributed power users whose installed capacity is larger than 10 kW. At the same time, the installed capacity of nodes 2、13、14、15、16、22 and 23 is 167.2 MW, 220 MW, 833.4 MW, 341 MW, 341 MW, 880 MW, and 341 MW, respectively. The data for the detailed generating equipment and power lines to be selected are shown in Tables 1 and 2, in which the investment cost of power lines is ¥683,880 ¥/km (Data source: Enterprise data). As for the running cost of the distributed generating equipment and the load of the power network, please refer to the literature (Ng et al.,

Table 1 Parameters of the distributed generating equipment

Node	Capacity/MW	Investment/ (¥10,000)
1	167.2	160.5
2	167.2	160.5
13	220	211.2
14	833.4	–
15	341	327.36
16	341	327.36
22	880	–
23	341	–

Table 2 Parameters of power lines to be selected

Branch	Maximum transmission power/MW	Quantity of existing lines	Length of line/km
1–3	175	1	55
2–4	175	1	33
7–8	175	1	16
13–12	500	1	66
15–24	500	1	72
16–14	500	1	54
21–18	500	1	36
23–20	500	1	30

2009). It is assumed that the mean on-grid price for users in the distributed system is ¥0.5/(kW·h) and the retail price of grid company is ¥0.657 /(kW·h) which is referring to the flat-section electricity price of large industrial users in Beijing City. There are 3 scenes totally for the analog simulation: scene 1 is about the independent decision making for the power grid and the distributed system without consideration of the game; scene 2 is about the combined decision making of the power grid-distributed system without consideration of game; scene 3 is about the combined decision making of the power grid-distributed system with consideration of game.

4.2 Simulation results analysis

The requirements of load for users in the distributed system in 3 scenes are the same. The comparison of power network decision-making results is shown in Fig. 6.

It is known from Fig. 6 that in the decision making of generating equipment, what scene 1 selected was the No. 1, No. 2, No. 7, and No. 15-node unit; what scene 2 selected was the No. 1, No. 2, No. 7, and No. 16-node unit; what scene 3 selected was the No. 1, No. 2 and No. 7-node unit. In the decision making of power lines, the difference of 3 scenes is as follows: in scene 2, power lines are newly constructed in all the branches to be selected; in scene 1, there are no newly constructed power lines in the 21–18 branches and 23–20 branches; in scene 3, there are no newly constructed lines in the 23–20 branches. The situations related to newly constructed power lines for the rest of branches are the consistent.

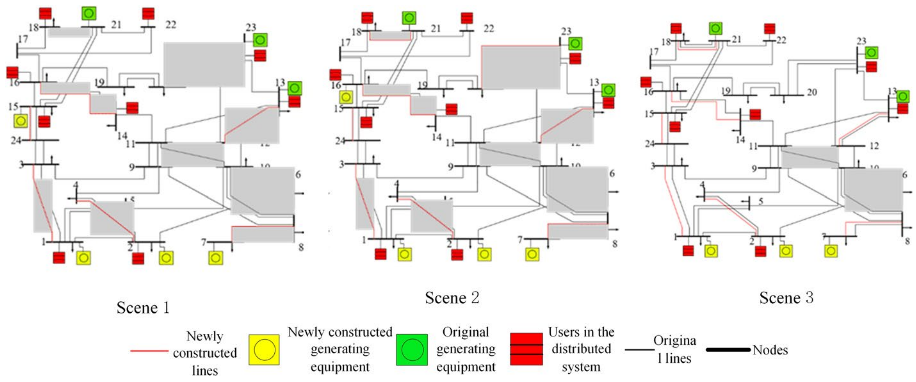

Fig. 6 Power network decision-making results

4.2.1 Comparison analysis of scene 1 and scene 2

A comparison of return in scene 1 and scene 2 is shown in Table 3.

It can be seen from Table 3 that the decision-making result of scene 1 is different from that of scene 2. Independent decision making is conducted in scene 1 while combined decision making is conducted in scene 2. Independent decision making differs from combined decision making in the aspect of the thinking in seeking the optimized target. Independent decision making refers to decision making by the distributed system and grid company separately, while combined decision refers to overall planning decision making by power grid-distributed energy system from the integrated angle.

As far as investment cost is concerned, the investment cost of grid company in scene 2 reduced by ¥41.03 million compared with scene 1. The reason is that the decision-making scheme was formulated with the optimized total revenue of power grid-distributed energy system as the target in the process of combined decision making in scene 2, and the number of expanded lines in the vicinity of the coupling nodes was less than that in scene 1 so that the investment cost of grid company was reduced.

As far as other several costs are concerned, compared with scene 1, the on-grid energy for the distributed energy system reduced in scene 2, with reduction of on-grid income by ¥27.60 million, reduction of the running cost by ¥1.88 million, reduction of environmental revenue by ¥9.60 million as well; the investment of grid company reduced, with reduction of power loss by ¥2.50 million. The generating cost and running cost for the distributed energy system were higher than that for the traditional coal-fired unit of thermal power. As for grid companies, the on-grid cost of the distributed energy was higher than that of thermal power, but generating pollution emissions for the distributed energy system was much less than that for the coal-fired unit, which would result in a reduction of environmental pollution drastically. The independent decision making in scene 1 was similar to the current practical situation. With the expansion of lines in the vicinity of the distributed energy system, a part of generating capacity would be transferred from the coal-fired unit to the distributed energy system, leading to the decrease in environmental cost. While consumption of the electricity network could increase because the expansion of lines could increase the total power transmission distance of the lines.

The total revenue in scene 2 increased ¥6.21 million compared with scene 1. The reason is that the independent decision making for the distributed energy and grid company

Table 3 Comparison of total return

Scene	Participant	Total income	Investment cost	Income from selling power of power grid	On-grid income/cost	Cost of power loss	Running cost	Environmental revenue	Total revenue
1	Distributed system	4015	1187		4015	0	269	1397	3956
	Power grid	5276	5378	5276	4015	375	0	0	− 4491
	Total	9291	6564	5276	8030	375	269	1397	− 535
2	Distributed system	1255	211		1255	0	81	437	1399
	Power grid	1649	1378	1649	1255	125	0	0	− 1108
	Total	2904	1589	1649	2510	125	81	437	291

Unit: ¥10,000

in scene 1 caused the failure of formulating comprehensively the best decision-making plan by overall planning coordination for its power load. Different from scene 1, the model in scene 2 might conduct overall planning coordination from the integrated angle of the power grid-distributed energy system. The formulated decision-making plan brought about a great reduction of investment cost and power loss cost of the grid company in scene 2, but also brought about reduction of load which was transferred from the coal-fired unit to the distributed energy system and reduction of environmental benefits. Therefore scene 2 can increase the total revenue of the system on the whole compared with scene 1.

The correction of coupling nodes was conducted by using the result of the current calculation in scene 1 and scene 2. The ultimate decision-making results in scene 1 and scene 2 were performed with mixed current calculations to judge whether to meet the requirement of power balance constraint of coupling nodes. The results in scene 2 passed the correction of coupling nodes, while 28.12% of nodes in scene 1 did not pass the correction. It is shown in Table 4.

In scene 2, the constraint conditions for the coupling nodes have been considered when decision making was conducted. While in scene 1, the distributed energy system and the grid company only considered the safety constraint conditions of their network separately,

Table 4 Correction situation of coupling nodes for the decision-making results

Time	Node							
	1	2	7	13	15	16	21	23
1	1	1	1	1	1	1	1	1
2	1	0	1	1	1	1	1	1
3	1	0	1	1	1	1	1	1
4	1	0	1	1	1	1	1	1
5	1	0	1	1	1	1	1	1
6	1	1	1	1	1	1	1	0
7	1	1	1	1	0	1	1	0
8	1	1	1	0	0	1	1	0
9	1	1	1	0	0	1	1	0
10	1	1	1	0	0	1	1	0
11	1	1	1	0	0	1	1	0
12	1	1	1	0	0	1	1	0
13	1	1	1	0	0	1	1	0
14	1	1	1	0	0	1	1	0
15	1	1	1	0	0	1	1	0
16	1	1	1	0	0	1	1	0
17	1	1	1	0	0	1	1	0
18	1	1	1	0	0	1	1	0
19	1	1	1	0	0	1	1	0
20	1	1	1	0	0	1	1	0
21	1	1	1	0	0	1	1	0
22	1	1	1	0	0	1	1	0
23	1	1	1	1	1	1	1	0
24	1	1	1	1	1	1	1	1

1 refers to pass, 0 refers to failure

Table 5 Various costs and revenues of the grid company

Scene	Total income	Power loss cost	Investment cost	Revenue from selling power
2	1649	125	1378	394
3	4310	325	3878	1030

Revenue from selling power = income from selling power-on-grid cost
Unit: ¥10,000

Table 6 Total revenue

Scene	Total income		Total revenue	
	Distributed system	Grid company	Distributed system	Grid company
2	2904	1649	1399	− 1108
3	7590	4310	3330	− 3173

Unit: ¥10,000

therefore the decision-making result in scene 1 might come with the situation which did not meet the requirement of constraint conditions for coupling nodes when running by combination.

4.3 Comparison analysis of scene 2 and scene 3

The decision-making results in scene 2 and scene 3 differed from each other although a combined decision was made in the two scenes. The reason is that in scene 2 the combined decision was made to maximize the total revenue. While in scene 3 the equilibrium state of the maximized revenue for participants was pursued by the dynamic game between the grid company and the distributed energy system, starting from individual rationality. Furthermore, the participants' adjusted strategies in time automatically in scene 3 based on blockchain technology. Therefore, the decision-making plan in scene 3 might differ from that in scene 2 without consideration of the game. In scene 2 and scene 3, the comparison of various costs and revenues of the grid company and the distributed energy system is shown in Tables 5 and 6.

Compared with scene 2, it can be seen from Table 3 that the investment cost in power lines in scene 3 increased by ¥26.61 million and the power loss cost increased by ¥2 million. In scene 3, the trading efficiency improved because the grid company and the distributed system based on blockchain technology-adjusted investment strategy in time after multiple subjects participated in the game.

Compared with scene 2, it can be seen from Table 6 that in scene 3, the revenue of the grid company was reduced by ¥19.31 million and the total revenue of the distributed energy system was reduced by ¥9 × 106. The reason is that in scene 2, the decision-making plan was issued unitedly to maximize the overall interests by which various investment subjects needed to abide, and the subjects failed to make independent decisions to obtain a better result for themselves only. As a result, in scene 2, the maximization of the overall revenue was based on losing environmental benefits and reducing the on-grid of the distributed energy.

In scene 3, the participants made independent decisions for the sake of their interests and in pursuit of the equilibrium game result satisfying various participants in the inter-constrained dynamic game process. Compared with scene 2, in scene 3 the total revenue decreased, but the decision-making plan considered the interests of all the participants. Therefore, the dynamic game decision-making plan conformed to the running mechanism of the distributed energy and ensured development motivation effectively.

5 Conclusion

The combined decision-making model of the power grid-distributed energy system is put forward in combination with the dynamic game theory based on consortium blockchain in the thesis, and the returned model of game subjects is built separately to establish the dynamic game model of the combined decision making. Finally, the model is solved by the iterative search method. The conclusion is as follows:

(1) The issues including investment chaos, resource waste, asymmetric information existing in the distributed energy system can be optimized by combination from power grid-distributed energy system.
(2) Overall planning modeling is studied from the integrated angle of power grid-distributed energy system, the game behaviors of many subjects are considered in the combined decision-making process, the interests of all the participants are considered in the manner of overall planning. Therefore, the formulated decision-making plan not only increases the total revenue of distributed energy system, on the whole, optimizing investment decision making but also ensures stable running of coupling nodes in safety effectively, which promote the development of distributed energy.
(3) Blockchain technology executes the game process automatically so that the whole decision-making process is in time, efficient, and in favor of optimizing the integrated benefit.
(4) By comparing the simulation results of typical examples in different scenarios, it can be seen that compared with independent decision making, joint decision making can increase the total benefit of the system as a whole. Compared with the joint decision making without the game, the joint decision-making method proposed in this paper takes into account the interests of all participants and is more in line with the operation mechanism of distributed energy. It provides an effective method for distributed energy to participate in power transaction-related decision making in the future.
(5) With the combination of blockchain and distributed energy, the rational allocation of resources through joint decision making can give full play to the maximum economic and social benefits of each subject, and help to further optimize the energy system. Furthermore, it provides a reference for government departments to formulate relevant energy policies to guide the enthusiasm of users to participate in distributed energy investment.

China has always adopted an incentive policy for distributed generation, and the promotion of the new power reform makes more and more subjects participate in the market transaction, which makes it possible for the electricity market transaction based on blockchain. It is necessary to further develop the market-oriented transaction of distributed generation and deepen the reform of the power system so that individuals and enterprises can become the main body of electricity sales. Simultaneously, a distributed energy transaction management system can be established in China including information systems, market mechanisms, and pricing mechanisms. The energy bilateral trading system is associated with the blockchain accounts of market participants to know the real-time demand and supply data of the participants. Based on these data, we can forecast consumption and power generation, and formulate relevant bidding strategies accordingly. Then the distributed energy market can operate efficiently by matching the sale and purchase orders of market participants to achieve the rational allocation of energy resources.

In the process of promoting the energy Internet, we should deeply tap all kinds of distributed resources and strengthen the interaction between the distributed energy system and the power grid. An energy system trading platform based on blockchain is constructed to realize the optimal scheduling among multi-systems. In the joint decision-making model of the power grid and distributed energy system proposed in this paper when making self-decision optimization, each system takes into account the interests of other systems, adjusts decisions regarding the information of other systems, and optimizes their respective investment decisions. It can achieve the result of optimal overall benefit, and at the same time improve the phenomenon of investment confusion, waste of resources, and information asymmetry in the development of distributed energy.

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Data availability In this paper, Table 1 distributed power generation equipment parameters and Table 2 transmission line parameters are set according to research needs. Data-related transmission line investments are based on investment and calculation of transmission line engineering units in Hunan Province, China. The calculation software is an independent research and development platform of the enterprise. The URL is: *http: //10.223.41.17: 18,080 / tempo / login.jsp* (this URL needs to run on the company's internal network). The platform collected cost information for nearly 5 years of transmission line project and analyzed eight influencing factors of the project, such as terrain, voltage grade, and wire type. The transmission line investment costs mentioned in this article "683,880 ¥/km" are calculated by the platform data. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to state restrictions such as privacy or ethical restrictions.

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