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Adaptability Among Power Source, Power Grid and Load Based on Game Theory

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Abstract: The coordinated development of power grid and load is one of the basic factors to optimize the social resources and to improve the equipment utilization. The decision makers of power grid and load are different. And their focuses are also different. These may result in a situation where the two partners may be missing each other in the development. And these may lead to the occurrence of idle equipment or waste of power supply. Therefore, improving the level of mutual adaptation of power grid and the load development is the necessary condition to promote the coordinated development of power grid and load. In this paper, a method is proposed to analyse the adaptability level of power grid and load. The method establishes a game model of power grid and load. And optimal power flow is applied to the analysis of interaction between power grid and load. Incomes of power grid and load in various strategies are calculated to establish the Nash equilibrium. These explain the behaviors of power grid and load and provide the basis for the decision. The proposed method is applied in two systems.

Keywords: Environment adaptability, game theory, load, optimal power flow, power grid.

1. INTRODUCTION

With the deepening market-oriented reform of electric power industry and the increasing power external environment constraints, grid coordination development issues have become increasingly prominent with the external environment. Considering the power side, conventional energy, such as coal, oil and natural gas, is running short, and social and economic development is facing serious challenges in terms of energy crisis, hence energy conservation, green energy and sustainable development become a focus of attention of the world. To achieve the sustainable development of energy resources and solve environmental problems, China has proposed to implement the efficient development of conventional energy intensively, as well rapid development of clean energy such as hydro, wind, solar and other renewable energy. Due to the characteristics of randomness, intermittency and volatility of renewable energy, it needs to be considered in network planning that whether the grid can meet a large-scale access to diversified power and submit a request.

On the load side, with the continuous development of the social economy, power grid development needs to adapt to the growth of the power load. In addition, the gradual rise of distributed power, micro-grid and electric vehicles also greatly impacted on power grid planning, operation and development. As for power grid planning, the impact of substations and transmission lines on the occupied station site, line corridor and the surrounding environment should be considered. Therefore, under the new situation of the national network and electricity market reform, evaluation is still in a traditional way that mainly considers grid security and economy. Grid planning ideas, which seldom consider adaptability between grid and its external environment such as energy resources, socio-economic development and environmental protection, will cause mismatch between power grid development and the external environment, such as social development and economic development *etc*. To make the grid optimize power generation resources configuration and meet the requirements of market transactions, there is an urgent need to propose an adaptive research on power grid, power supply and load, and this has great significance in achieving the coordinated development between the grid, power and load [1-4].

In the adaptive analysis of coordination between grid and the external environment such as power supply, traditional network planning methods often use security and economy or other indicators of the grid. Using traditional optimization methods, generally taking grid economy as optimization an goal, and grid security and the given external conditions as constraints, analytical methods are used for the analysis [5-9]. It is relatively clear that this method affects the factors of the external environment. And when constraints are used as given boundary conditions for solving the optimization, good results are achieved. But under conditions of market economy, due to various factors of the external environment such as power supply, generation companies, transmission companies, user sides, and other participants, on one hand, industries seek to maximize their own economic interests, on the

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other hand, the key development strategies such as trade secrets are generally not open in other industries. With the external environment changing, power, users and other participants undertake ongoing policy adjustments, and there exists a game behavior with the grid, where the resulting grid constraints are no longer identified and are easily accessible. Therefore, it is not appropriate to use the traditional optimization methods, but game theory can solve the problem better. Currently, game theory has been applied in the power sector, but mainly focuses on resolving line blocking problem and bidding game among generation companies [10-13], study of trilateral game among power supply, power grid and load, is to a limited extent. Hinted by a game-theory-based research on development suitability between grid and load, in this paper, a method using game theory is proposed to study adaptability among the power, grid and load, and the effectiveness of such method is illustrated by a simple numerical example.

2. GAME THEORY AND NASH EQUILIBRIUM

Game theory is the study of how to optimize their decision-making theory when there is mutual restraint or interest conflict between multiple decision-making bodies. Its main feature is that the ultimate income participants obtained depend not only on strategies they selected, but also on behavioral programs implemented by other participants. Participants, strategies, strategies order and the income are four components of the game. In the course of the game, assuming that each participant is rational, who is always seeking to maximize their biggest gains in any situation. Multi-Game expression is usually expressed as:

$$G = \{S_1, S_2 \cdots, S_n; u_1, u_2, \cdots u_n\} \tag{1}$$

In the formula (1), n is the number of participants; u_i represents revenue function of participant i; $S_1, S_2 \cdots, S_n$ represents the policy space for each participant.

Nash equilibrium can be expressed as:

$$\begin{aligned} & u_i(s_1^*, \cdots, s_{i-1}^*, s_i^*, s_{i+1}^*, \cdots, s_n^*) \geq \\ & \quad u_i(s_1^*, \cdots, s_{i-1}^*, s_i, s_{i+1}^*, \cdots, s_n^*) \end{aligned} \tag{2}$$

Being established for all $s_i \in S_i$.

That is: in the game $G = \{S_1, \cdots, S_n; u_1, \cdots u_n\}$, in the composition of each strategy chosen by the participants, if there exists a policy combination $(s_1^*, \cdots, s_n^*)$ that strategy of either participant i is s_i^* and its corresponding income $u_i(s_1^*, \cdots, s_{i-1}^*, s_i^*, s_{i+1}^*, \cdots, s_n^*)$ is always greater than or equal to $u_i(s_1^*, \cdots, s_{i-1}^*, s_i, s_{i+1}^*, \cdots, s_n^*)$, then $(s_1^*, \cdots, s_n^*)$ is called a Nash equilibrium [13] of the game G. Power, grid and load, as major components of the power system, are participants in the process of the game. In a market environment, there is A mutual link between power consumption and price. But each participant's investment is different in terms of the object and focus, and investment income of the parties is affected by others' decisions, as game relationship exists between them. Among them, the power generation invests power supply (power plant); the key concern includes motor investment cost, motor operation and maintenance costs, and revenue brought by increasing the electric power generation. Power grid invests the transmission lines and transformers,; their concern is focused on the power equipment investment cost, operation and maintenance costs, and revenue brought by the increase of power in sales after equipment inputted. All participants select their optimal strategy, maximizing their own interest, so as to arrive Nash equilibrium strategy combinations.

3. GAME MODEL OF PARTICIPANTS

To better describe the game behavior of each participant under the market environment, based on the electric power system characteristics, using a simultaneous game mode between participants, investment returns are converted into the same economic evaluation within the year. Electricity market uses nodal price model and rigid load, where the system is dispatched by Independent System Operator (ISO).

3.1. Generating Model

In order to adapt to the needs of the development of load, according to the new grid power capacity and load demand, generation side needs to decide the new unit capacity, their strategy goal is to maximize their profits through the new proper capacity, the model is as follows:

$$\max_{P_{g.k}^{new}} \{\rho_k P_{g.k} - C_{invg} P_{g.k}^{new} - C_{opg} P_{g.k}^{new}\} \tag{3}$$

$$s.t.\ \ 0 \leq P_{g,k} \leq P_{g,k}^{new} \tag{4}$$

In the formula (3), ρ_k represents the power price of node k; $P_{g,k}^{new}$ is the output of the new power supply; C_{invg} is the investment cost coefficient of the new power supply; C_{opg} is the run price coefficient of the new power supply.

Formula (3) is the objective function of grid model, it represents the power generation's profit after investing power plant. In the objective function, the new motor installed capacity of node k $P_{g,k}^{new}$ and its actual output $P_{g,k}$ are the decision variables of the optimization problems. Formula (4) shows inequality constraints of motor output.

3.2. Grid Model

The grid includes lines and transformer which are two main parts to meet the needs of the development of load. The grid, on one hand, needs to add some substation capacity, on the other hand, it can choose whether to invest transmission lines.

We set grid node k to increase substation capacity to T_k, grid square strategy goal is to maximize their profits by selecting proper substation capacity and choosing whether to invest line *Lmn*. The model is as follows:

$$\max_{T_k}\{(\sum_{i\in N}\sum_{j\in N}(\rho_j-\rho_i)F_{ij}^{'}-C_{opl}F_{ij}^{'}) \\ +C_tP_{d,k}^{new}-C_{opt}T_k-C_{invt}T_k\},\ \forall F_{ij}\ge 0 \tag{5}$$

$$\max_{T_k}\{(\sum_{i\in N}\sum_{j\in N}(\rho_j-\rho_i)F_{ij}-C_{opl}F_{ij})-C_{invl}F_{mn}- \\ (\sum_{i\in N}\sum_{j\in N}(\rho_j-\rho_i)F_{ij}^{'}-C_{opl}F_{ij}^{'}) \\ +C_tP_{d,k}^{new}-C_{opt}T_k-C_{invt}T_k\},\ \forall F_{ij}\ge 0 \tag{6}$$

$$s.t.\ \ 0\le P_{d,k}^{new}\le \min(T_k,D_k) \tag{7}$$

Formula (5) is the return model of grid square when grid transmission line does not extend. Formula (6) is the return model after extending line *Lmn*. In the formula, N is the number of nodes in the system; ρ_i and ρ_j, each represents node power price of node *i* and *j respectively*; $F_{ij}^{'}$ represents the branch power flow from node *i* to *j* when grid transmission line does not extend; F_{ij} is the branch power flow from node *i* to *j* when extending the line *Lmn*; *Fmn* represents line capacity of line *Lmn*; C_{invl} is the investment price coefficient for extending line *Lmn*; C_{opl} is the run price coefficient of transmission line; $P_{d,k}^{new}$ is the increasing load transfer volume of node k; C_t is the price coefficient of the new increasing load transfer volume; T_k is the new increasing substation capacity of node k; C_{opt} is the run price coefficient of the new increasing substation capacity; C_{invt} is the investment price coefficient of the new increasing substation capacity.

Formula (7) shows constraint inequalities of grid model; it represents that the new load transfer volume of node k $P_{d,k}^{new}$ is limited by the new substation capacity T_k and the new load capacity D_k. The actual amount of added load transfer $P_{d,k}^{new}$ must be smaller than the minimum value of the new substation capacity T_k and the new load capacity D_k.

3.3. Load-Side Model

With economic developing, power users usually increase productivity by expanding the scale of production, thereby getting greater benefits. Setting the new load capacity of node k to D_k, the strategy of load side is to select appropriate load capacity to maximize its revenue; the mode is as follows:

$$\max_{D_k}\{C_sP_{d,k}^{new}-\rho_kP_{d,k}^{new}-C_{opd}D_k-C_{invd}D_k\} \tag{8}$$

$$s.t.\ \ 0\le P_{d,k}^{new}\le \min(T_k,D_k) \tag{9}$$

In formula (8), C_s is the output price coefficient of the new load capacity; ρ_k is the node power price of node k; D_k is the new load capacity of node k; C_{opd} is the run price coefficient of the new load capacity; C_{invd} is the investment price coefficient of the new load capacity.

Formula (9) shows constraint inequalities of load model; it represents that the new load transfer volume of node k $P_{d,k}^{new}$ is limited by the new substation capacity T_k and the new load capacity D_k. The actual amount of added load transfer $P_{d,k}^{new}$ must be smaller than the minimum value of the new substation capacity T_k and the new load capacity D_k.

3.4. ISO Scheduling Model

In this paper, power market uses the node price model, this model is widely applied in the world because it is relatively fair. First, each generation companies offer ISO their output quote. Then, based on the constraint conditions such as network security, taking the minimum social cost of production as the goal, ISO arranges the generator output, and its model is as follows:

$$\min\{\sum_{i\in N_g}C_iP_{g,i}\} \tag{10}$$

$$s.t.\ \ \mathbf{e}^{\mathbf{T}}(\mathbf{P_G}-\mathbf{P_D})=\mathbf{0} \tag{11}$$

$$\mathbf{T}(\mathbf{P_G}-\mathbf{P_D})\le\mathbf{F} \tag{12}$$

$$\mathbf{P_{G-}}\le\mathbf{P_G}\le\mathbf{P_{G+}} \tag{13}$$

In formula (10), N_g is the number of generators in the system; C_i is the output quote of generators *i*; $P_{g,i}$ is the actual output of generators *i*; $\mathbf{P_G}$ is the generator output matrix; $\mathbf{P_D}$ is the load matrix; $\mathbf{e}^{\mathbf{T}}$ is the system correlation matrix; $\mathbf{T}$ is the system branch power flow and the generator output sensitivity matrix; $\mathbf{F}$ is the system branch power load matrix; $\mathbf{P_{G-}}$ and $\mathbf{P_{G+}}$ each represent the upper and lower matrix of generators output.

Formula (10) is the objective function of the ISO model; it represents social total production cost. In this objective function, each generator's output $P_{g,i}$ is the decision variable of the optimization problem. Formula (11) shows the active power constraints of the system. Using DC power flow model, this paper mainly considers active power problem. Formula (12) is the DC power flow constraints of lines, representing the power flow of the line which is restricted within a certain range. Formula (13) shows the output constraints of generators; it represents the output of generators is restricted within a certain range.

3.5. Algorithm Process

In this paper, algorithm process is shown in Fig. (**1**).

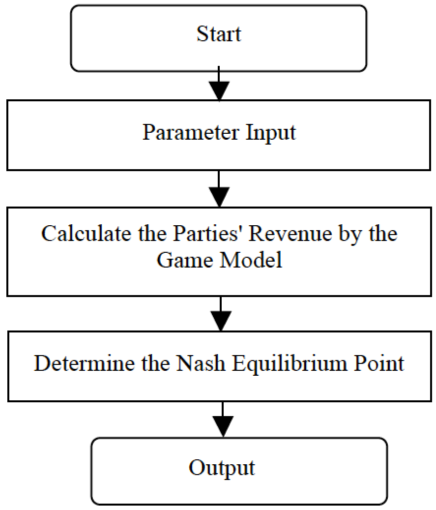

Fig. (1). Algorithm flow chart.

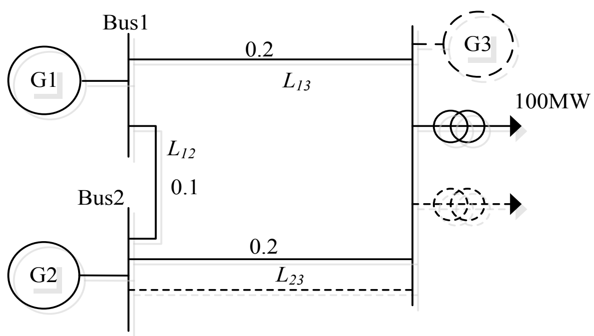

Fig. (2). Three-bus power system.

Table 1. Generator parameters.

Number	Bus	Upper Limit (MW)	Lower Limit (MW)	Bidding (S/MW)
1	1	0	200	10
2	2	0	100	12
3	3	0	–	14

4. THE EXAMPLE ANALYSIS

In this paper, a three -node system is analyzed, its wiring diagram is shown in Fig. (**2**). The system includes two generators G1 and G2, located at bus 1 and bus 2, respectively, and bus 3 is the load center; G_1 and G_2 transmit power to the load center bus 3 through the line L_{12}, L_{13} and L_{23}. Its generator parameters and line parameters are shown in Table **1** and Table **2**.

In this example, the initial load of bus 3 is 100MW and step-down transformers' download capacity is at full load. At this stage, the enterprise in bus 3 region will further expand the production, which increases the power demand , thus increasing the load of bus 3 . For power generation side, because the load of bus 3 increases, it can add a new power supply at bus 3, elevating the power of bus 3. For grid side, according to the load power demand, it can set a new transformer at bus 3, at the same time, because there are transmission capacity constraints in line L_{13} and L_{23}, grid side also can invest the extension line L_{23} to occupy bus 3 market. Therefore, in the bus 3, between the three participants, power generation side, grid side and load side, there is a game relationship between the problem of each new capacity. Each participant's investment information is shown in Table **3**.

For power generator side G_3, its three optional strategies include, not to invest, to invest 50MW generators, and invest 100MW generators. Generator economic parameters are shown in Table **4**.

Table 2. Line parameters.

Number	Bus i	Bus j	Admittance	Capacity(MW)
1	1	2	0.1	100
2	1	3	0.2	80
3	2	3	0.2	80

Table 3. Participants' investment information.

Participants	Investment Object	Capacity(MW)	Strategy Code
Power Generation Side(U_1)	G3	0	0
		50	1
		100	2
Grid Side(U_2)	Not invest line	–	0
	L_{23}	–	1
	T_2	90	0
		110	1
		130	2
Load Side(U_3)	Low-energy Industry	100	1
	High-energy Industry	120	2

Table 4. Generator economic parameters.

Parameter	Unit	Parameter Values
Copg	$/MW	0.1
Cinvg	$/MW	12

Table 5. Grid economic parameters.

Parameter	Unit	Parameter Values
Ct	$/MW	20
Cop*L*	$/MW	0.01
Cinv*L*	$/MW	0.5
Copt	$/MW	0.1
Cinvt	$/MW	10

Table 6. User economic parameters.

Parameter		Unit	Parameter values
Cs	Low strategy	\$/MW	35
	High strategy	\$/MW	30
Copd		\$/MW	0.2
Cinvd		\$/MW	11

Table 7. Strategy profiles and payoff vectors.

Stages	Profit(μ_1, μ_2, μ_3)
(0,(0,0),1)	(0,930,-670)
(0,(0,0),2)	(0,930,-1194)
(0,(0,1),1)	(0,728,-670)
(0,(0,1),2)	(0,728,-1194)
(0,(0,2),1)	(0,526,-670)
(0,(0,2),2)	(0,526,-1194)
(0,(1,0),1)	(0,1448,770)
(0,(1,0),2)	(0,1448,960)
(0,(1,1),1)	**(0,1646,980)**
(0,(1,1),2)	(0,1646,416)
(0,(1,2),1)	(0,1244,980)
(0,(1,2),2)	(0,1244,576)
(1,(0,0),1)	(-65,1009,410)
(1,(0,0),2)	(-65,1009,-264)
(1,(0,1),1)	(115,1007,580)
(1,(0,1),2)	(693,1481,-899)
(1,(0,2),1)	(115,1005,580)
(1,(0,2),2)	(693,1279,-899)
(1,(1,0),1)	(-605,888,950)
(1,(1,0),2)	(-605,888,276)
(1,(1,1),1)	(-605,886,1180)
(1,(1,1),2)	(-605,1086,636)
(1,(1,2),1)	(-605,684,1180)
(1,(1,2),2)	(-605,1084,816)

Table **7**. contd…

Stages	Profit(μ_1,μ_2,μ_3)
(2,(0,0),1)	(-549,1009,410)
(2,(0,0),2)	(-670,1009,-264)
(2,(0,1),1)	(-490,1007,580)
(2,(0,1),2)	(-310,1207,-24)
(2,(0,2),1)	(-490,805,580)
(2,(0,2),2)	(-130,1205,96)
(2,(1,0),1)	(-1089,888,1130)
(2,(1,0),2)	(-1210,888,456)
(2,(1,1),1)	(-1210,1048,1254)
(2,(1,1),2)	(-1160,1886,416)
(2,(1,2),1)	(-1210,846,1254)
(2,(1,2),2)	(-1080,1884,576)

The grid side, according to power demand of load side, has six optional strategies, which are, (not to invest lines, invest 90MW transformer), (not to invest lines, invest 110MW transformer), (not to invest lines, invest 130MW transformer), (invest line L_{23}, invest 90MW transformer), (invest line L_{23}, invest 110MW transformer), (invest line L_{23}, invest 130MW transformer). Grid economic parameters are shown in Table **5**.

For load side, based on the production technology, there are two strategic choices, low energy consumption industry strategy and high energy consumption industry strategy. Low energy consumption industry strategy includes adding 100MW new electricity load belonging to technology upgrading plan, with a high product value. High energy consumption industry strategy includes adding 120MW new electricity load, which belongs to high energy consumption program, with a low product value. Economic parameters of load side strategy are shown in Table **6**.

Synthesizing all participants' investment strategies, the pure strategy space of the game contains 36 strategies, each participant's income under various combinations can be derived through the game model, shown in Table **7**.

It can be known through traversing method that there is only one Nash equilibrium point in the game, its strategy combination is: S^*=(0,(1, 1), 1). That is: power generator side does not make any investment, transmission side invests line and adds a new 110MW transformer, and the load side uses low power consumption technology upgrade program. The result obtained shows that for power generator side, because the new power plant is built in the load center of bus 3, after years of development, this region is densely populated, with high land requisition and small allowance for environmental emissions, causing that the cost of the new power plant G3 is higher than G1 and G2. According to ISO scheduling model, G3 provides power to load only in the case of transmission lines fully loaded or with G1 and G2 , otherwise G3's output is zero, its corresponding income is zero or negative). Therefore, the profit of power generator side is affected by investment strategy of grid side and load side. If the grid side does not invest in the transmission line and adds a 130MW transformer, load side will take high energy consumption strategy. Following this, the power generator side builds a new power plant so as to maximize revenue (combination (1,(0, 2), 1)). But for grid side, whether load side adopts high or low energy consumption industry strategy, the profit of 130MW transformer they invested is less than 110MW transformer; that is because the grid side is given high substation capacity, causing extra substation capacity, thus reducing its earnings. In addition, in order to occupy the market of bus 3 load zone, taking the advantage of low power plant construction cost of bus 1 and 2, grid side will invest transmission line L_{23} to maximize their interest; this makes the optimal strategy of power generation side deviated from the original construction of 50 mw power plant, and choose not to do any investment. For load side, their choice of the optimal strategy will also be affected by the strategy of the power generator side and grid side choice, although they both can obtain the biggest benefit 1254$ from the strategy combination (2,(1,1),1) and (2,(1,2),1), but to pursuit its best interests, power generator side will not invest power plant G3, correspondingly, load side cannot obtain the biggest benefit for 1254$. In the situation of power generator side choice strategy 0 and grid side choice strategy (1,1), only low energy consumption strategy (that is strategy 1) can maximize their profits. Integrating the strategy of power generator side, grid side and load side, is a pure strategy combination that meets the Nash equilibrium condition, where the three participants are unwilling to deviate from the equilibrium point alone. This combination is consistent with

China's current development direction: "grid appropriately exceeding development", "break-place balance, long-distance transmission", "eliminating backward production capacity".

CONCLUSION

1) In this paper, based on game theory, the development adaptability analysis method of power supply, grid and load is proposed that fully considered the impact of electricity market reform on the power system planning, and can guide grid planning to effectively overcome the shortage of traditional methods.

2) In this paper, based on the different focus of power generator side, grid side and load side when planning and running power system, their own game model has been established respectively, and the quasi-steady state sensitivity method, which is based on DC power flow, is used to calculate node power price. In order to obtain the participant's income in the market environment for different strategies, the Nash equilibrium point is determined. The research results show the correct development direction of China's current stage: "grid appropriately exceeding development", "break-place balance, long-distance transmission", "eliminating backward production capacity".

CONFLICT OF INTEREST:

The authors confirm that this article content has no conflict of interest.

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