Multi Agent Participation in Renewable Energy Consumption Considering Evolutionary Game Theory

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Abstract: Intermittence and randomness of renewable energy such as wind and light limit the consumption of renewable energy. Nowadays, with the development of many flexible resource technologies, such renewable energy is able to be used for peak shaving and frequency modulation, which makes it possible to utilize more renewable energy. After the formation of the power market pattern of "separation of power plant and power grid", many flexible resources participate in the game competition of main energy market and auxiliary service market at the same time. Under the condition of information disclosure, the traditional game theory makes the main agent achieve Nash equilibrium after a game, which is obviously not in line with the reality. Therefore, based on evolutionary game theory, this paper discusses the evolutionary stable equilibrium of traditional power generation enterprises, new energy enterprises and energy storage enterprises over time, which is called refined Nash equilibrium. Firstly, according to the replication dynamic equation, the evolutionary game model of renewable energy consumption is established. Then, the genetic algorithm is applied to the calculation of the proposed renewable energy consumption evolutionary game model. Finally, the effectiveness of the evolutionary game model is verified by using England 39 bus system.

1. Introduction

Nowadays, the world is facing such crises as fossil fuel depleting and environmental polluting. Traditional power is bound to be replaced by wind power, PV and other energies that is no-pollution and no-consumption. By the end of 2019, traditional power almost accounted for the vast majority of electric quantity in the world. Renewable energy consumption only accounted for 7.7% of total power and the consumption capacity is ranking almost the lowest in the world. Therefore, it is particularly important to improve enthusiasm of power source-power grid-load-stored energy and other flexible resources[1] to participate in market competition and assist in consumption of renewable energy.

With the issuance of Several Opinions on Further Deepening Reform of the Electric Power System[2] in China in 2015, the power generation side and the load side participate in market competition gradually, which breaks monopoly of State Grid. Thus, the pattern of power market has taken shape initially. Many flexible resources (including conventional energy (CE), renewable energy (RE), stored energy (SE), demand response (DR)) participate in power market competition, which has changed original time-space characteristic of electric energy and beneficial for consumption of renewable energy. However, with reform of power market, government can no longer intervene behaviors of each market agent. How to use market mechanism to promote action of each type of flexible energy and profit consumption of renewable energy need to be settled immediately.

Flexible resource participating in power market competition is a process during which multi agents game with each other to balance interests of all parties need to be concerned. The balance is called Nash equilibrium. After that, mathematic models of mutual game of multi agents have been proposed. Reference[3] has proposed game model of conventional power generation enterprises, renewable energy enterprises and energy storage enterprises. Transfer reinforcement learning algorithm is used for solving it. However, decision information made by other parties need to be obtained from the information center during the game process, which is difficult to realize in the real situation. In view of this, reference[4] has proposed power market model under game with incomplete information completely and utilized coevolution algorithm to solve corresponding Bayesian Nash equilibrium. Although the reference has discussed game behaviors with limited information, it still researches on the basis that decisions made by the game part is rational. In allusion to multi agent game research of “Bounded rationality and limited information”, evolutionary game theory (EGT) mathematical theory is conducted generally. It’s believed in EGT that on the basis of “Bounded rationality and limited information”, Nash equilibrium is always not generated in a time. It’s formed through social selection after many times of game with evolution of time. Currently, EGT is fully utilized in microgrid dispatching[5], power generation side bidding[6], thermal power peak shaving[7], demand side management[8-9] and green certificate trading[10]. Reference[11] will discuss bidding behaviors of power generation companies in southern areas and power grid. The evolutionary stability strategy of provincial grid company and power generation companies will be obtained through solving the multi-population replication dynamic equation. Dynamic simulation will be conducted for bidding behaviors of heterogeneous power generation companies and initial conditions necessary for realizing the stability strategy in[12], which will be analyzed from the perspective of evolution. Evolutionary game and coevolution algorithm will be combined together to solve economic conflicts between power grid and microgrid in[13]. A new power source-stored energy planning method jointly invested by operators in[14], which will be proposed in power distribution network and microgrid .Evolutionary game theory is used to solve “complete rationality” limit of game parties. Compared with traditional game theory, it can balance benefits of game parties in a better way.

Renewable energy consumption of flexible resources under information barriers hasn’t been discussed in existing researches. Based on this, this paper has researched decision-making behaviors of many flexible resources participating the main energy market and auxiliary service market at the same time. Firstly, an evolutionary game model will be established with many agents participating in renewable energy consumption; secondly, the evolutionary game model will be solved with genetic algorithm according to replication dynamic equation under each strategy in the enterprise. Finally, the limit of consumption of renewable energy will be analyzed according to the results of stability strategy.

2. Evolutionary Game Model of Renewable Energy Consumption

The paper builds a three-party game model by taking into consideration of economy of CE, RE and SE. It is assumed that CE has N units. $c^c_{i,t}$ is start or stop variable of unit i and output of unit i is $P^c_{i,t}$. RE has M units. $c^r_{i,t}$ is start and stop variable of wind turbine or PV units i and output of unit i is $P^r_{i,t}$. SR has L batteries for discharging. $c^s_{i,t}$ is charging or discharging state of each battery (1:charging, 0:off-grid, -1:discharging) and $P^s_{i,t}$ is capacity of each battery.

2.1. Modeling Analysis of Economy

2.1.1. Objective Function

As for CE, the earnings should be considered include on-grid energy earnings I_a^c, AGC auxiliary service compensation earnings I_b, start or stop peak shaving earnings I_c, in-depth frequency modulation earnings I_d and cold standby earnings I_e. According to "Two detailed rules" issued by the Bureau of Energy [15], the cost includes generation cost C_a, start and stop cost C_b and response cost C_c. Aforementioned parameters are functions of $c^c_{i,t}$ and $P^c_{i,t}$. Auxiliary compensation expenses C_d is paid to other enterprises (action information of other parties are required when calculating the parameter). Then, benefits of CE can be obtained as follow.

$$F_1(c^c_{i,t}, P^c_{i,t}) = I^c_a + I_b + I_c + I_d + I_e - C_a - C_b - C_c - C_d \tag{1}$$

As for RE, earnings should be considered include on-grid energy earnings I_a^r and limited power auxiliary service earnings I_f. The generation of RE doesn't have cost. Only operation cost C_f and auxiliary service compensation expenses paid to other companies C_g are considered. Aforementioned parameters are related to $c^r_{i,t}$ *and* $P^r_{i,t}$. Then, the benefits of RE can be obtained as follow.

$$F_2(c^r_{i,t}, P^r_{i,t}) = I^r_a + I_f - C_f - C_g \tag{2}$$

As for SE, the earnings is consist of auxiliary service compensation Ig (as per capacity and electric quantity). Cost includes operation and maintenance cost Ch, replacement cost Cj and power purchase cost Ck. Aforementioned parameters are related to csi,t and Psi,t Then, the benefits of SE can be obtained as follow.

$$F_3(c^s_{i,t}, P^s_{i,t}) = I_g - C_h - C_j - C_k \tag{3}$$

2.1.2. Constraint Condition

The aforementioned variables have to satisfy their own operation constraints and network transmission capacity limit. The detailed constraint condition can be obtained in[3].

2.2. Evolutionary Game Model

It is assumed that CE, RE and SE have A, B and C strategies. Each strategy is comprised of decision variable of each part. Extraction probability of each strategy of CE (individual proportion) is $p_1,p_2,\ldots p_A$. Extraction probability of each strategy of RE is $q_1,q_2,\ldots q_B$ and extraction probability of each strategy of SE is $l_1,l_2,\ldots l_C$. And then, replication dynamic equation can be obtained as follow.

$$\frac{dp_i}{dt} = p_i(\sum_{j=1}^{B}\sum_{k=1}^{C} q_j l_k F_1(p_i,q_j,l_k) - \sum_{i=1}^{A}\sum_{j=1}^{B}\sum_{k=1}^{C} p_i q_j l_k F_1(p_i,q_j,l_k)) \tag{4}$$

$$\frac{dq_j}{dt} = q_i(\sum_{p=1}^{A}\sum_{k=1}^{C} p_i l_k F_2(p_i,q_j,l_k) - \sum_{i=1}^{A}\sum_{j=1}^{B}\sum_{k=1}^{C} p_i q_j l_k F_2(p_i,q_j,l_k)) \tag{5}$$

$$\frac{dl_k}{dt} = l_k(\sum_{p=1}^{A}\sum_{j=1}^{B} p_i q_j F_3(p_i,q_j,l_k) - \sum_{i=1}^{A}\sum_{j=1}^{B}\sum_{k=1}^{C} p_i q_j l_k F_3(p_i,q_j,l_k)) \tag{6}$$

The bus of evolutionary strategy can be obtained by solving zero point of aforementioned equation. According to analyze characteristic value of Jacobian matrix of aforementioned equation with Lyapunov's principle, the bus can be determinedto stable or not. If the characteristic value is negative, the zero point obtained is evolutionary strategy stablone, which is reaching perfect Nash equilibrium.

3. Genetic Algorithm

Genetic algorithm is designed by American John Holland according to law of biological evolution of nature. It's a method simulating natural law of "Natural selection, survival of the fittest" and searching for the optimum solution. To realize aforementioned multi agents participating in consumption evolutionary game optimization process, this paper proposes an evolutionary game genetic algorithm based on multi agent participation consumption, which combines genetic algorithm with multi agent game process and to realize multi agent participation consumption optimization process based on this algorithm. In detail, maximum fitness individuals are searched through individual evaluation, selection, crossover, mutation and other operations.

N populations refer to game members of conventional power plants, renewable energy power plants, and energy storage enterprises, i.e., N=3. Each individual in population i represents one strategy, and the coding method for population i is as follows.

$$X_{op,i} = (x_1,x_2,\ldots,x_M)^T \quad i=1,2,\ldots N \tag{7}$$

where M is initialized population size, xi represents the decision variable of population i, i.e., the game player.

The steps of the evolutionary genetic algorithm are listed as follows:

1) Construct the game populations. N game parties can determine the range of decision variables based on renewable energy output prediction, load prediction, and operating states of themselves. Then the M strategic individuals are randomly generated and constitute the game populations. Individuals who do not participate in the evolutionary game can adopt fixation strategies.

2) Game-crossover among populations. Individuals are randomly selected from each population for game-cross. The game party can make better decisions based on the previous game result. The benefits of individuals should be calculated based on (1)-(3) after each game. Then the expected revenue of individuals can be obtained after K repeated games.

3) Individuals evolve in the population. Utilizing the genetic algorithm, each population shall simulate the processes of biological evolution and search for the optimum solution，which includes:

① Individual ranking: individuals within a population are ranked according to expected revenue.

② Selection operation: Select S pairs of individuals according to the ranking result and choose the ones who can adapt to the environment.

③ Crossover operation: for each individual from ② , select a gene point probabilistically and perform crossover.

④ Mutation operation: select individuals from small populations and randomly choose the spot on gene segments for inversion operation. The process is a simulation for biological gene mutation.

4. Numerical Results

To verify the validity of the evolutionary game model proposed in the paper, England 39-bus system is adopted for numerical analysis. The installed capacities of thermal power units and wind power units which are connected to bus 20 are respectively 1,662MW and 400MW. The capacity of energy storage is 520MWh and the power is 30MW. The auxiliary service compensation expenses are shown in Table 1, and other operating parameters and fuel consumption coefficients can be found in[3]. The dispatching period is 24h and the time resolution is 1h. The typical load power curve and renewable energy output curve are illustrated in Figure 2. The maximum power of load and wind are respectively 1,499MW and 312MW and are set as base values for per unit calculation.

Table 1: Compensation expenses for auxiliary services for conventional power supply units.

Auxiliary service compensation type	Unit	Expenses
AGC service capacity compensation standard	Yuan/MWh	3.56
AGC service electric quantity compensation standard	Yuan/MWh	29.2
Start and stop peak shaving compensation	10,000 yuan/10,000kW (installed capacity)	1.04
Deep peak shaving compensation (40%-50%)	Yuan/MWh	10.59
Deep peak shaving compensation (below 40%)	Yuan/MWh	21.18
Spinning reserve compensation	Yuan/MWh	3.53
Cold standby compensation	Yuan/MWh	2.5
Renewable energy power restricting compensation	Yuan/MWh	15
Storage capacity compensation expenses	Yuan/MWh	3.26
Storage electricity compensation expenses	Yuan/MWh	20

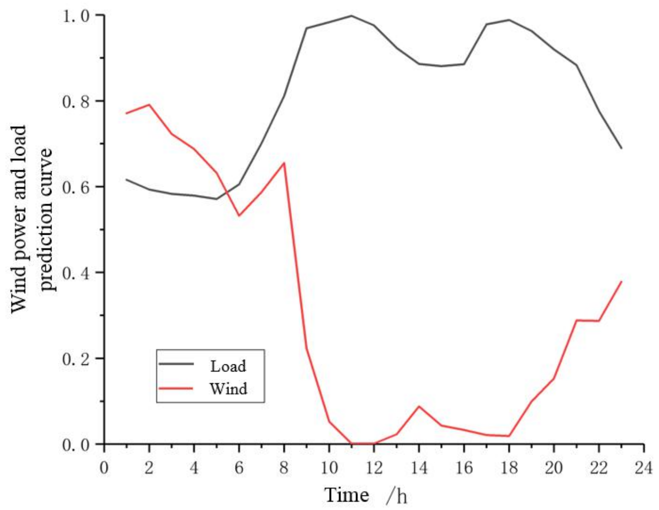

Figure 1: Wind power and load prediction curve.

4.1. Parameters Setting of Genetic Algorithm

The number of initial individuals should be large to reflect that the enterprises have many strategies for the mutual game, so we set N=50. And the maximum game repeating times K is set as 3000 and the maximum evolution iteration for population evolution G_{max} is 200. The fitness-proportionate selection is adopted and is set as 0.4, and the probability of crossover and mutation are respectively set as 0.6 and 0.8. The game is conducted hourly and the expected revenue is calculated.

4.2. Analysis of Evolutionary Game Result

Suppose that thermal power, wind power, and storage are three parties participating in market competition, and after constant learning of game strategy under the condition of information and rational barrier, the final evolutionary stable strategy can be achieved shown in Figure 2.

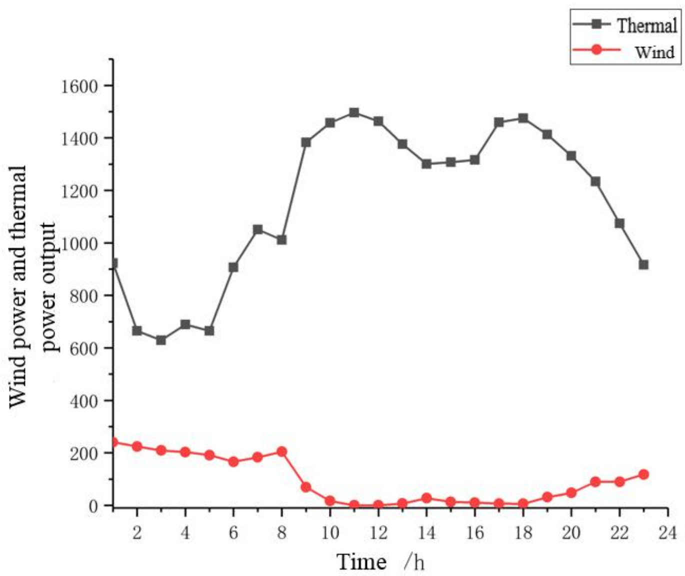

Figure 2: Wind power and thermal power output.

4.3. Analysis of Consumption Condition

Wind curtailment rate is generally used to evaluate the renewable energy accommodation for an area, which is defined as (Total wind power prediction – wind power consumption)/Total wind power prediction[16]. The wind curtailment rate is 2.5% on the aforementioned typical day, indicating that wind and PV power curtailment could be reduced if flexible resources are utilized. In addition, when wind power output is relatively high, deep peak shaving (below 40%) with thermal power units is helpful for renewable energy consumption.

5. Conclusion

This paper uses evolutionary game theory in renewable energy accommodation analysis with multi-agent participation. The economics of conventional power plants, energy storage enterprises and renewable energy power plants are analyzed, and based on their economies, the optimal action decisions are made through constant learning of strategies of other competitors under the condition of "Bounded rationality and limited information". Numerical results demonstrate the validity of the evolutionary game model for renewable energy accommodation. In this paper, the stable decision of all flexible resources are reached only under the condition of information barrier, the correlation between evolutionary stability strategy and initial conditions are not considered. For our future work, the correlation between initial states of flexible resources and the final evolutionary stable strategy will be considered to find the bottleneck of restricting renewable energy consumption.

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