IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 4, 2021, accepted November 15, 2021, date of publication November 25, 2021,
date of current version December 3, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3130577

New Energy Wide Area Complementary Planning Method for Multi-Energy Power System

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This work was supported in part by the National Key Research and Development Program of China under Grant 2017YFB0902200, and in part by the Science and Technology Project of State Grid Corporation of China under Grant 5228001700CW.

ABSTRACT Vigorously developing new energy is an important measure to deal with the energy crisis and environmental degradation, but the volatility and randomness of its output have brought great challenges to the new energy consumption. In this paper, the maximum new energy consumption is taken as the objective function, and the power flow constraints, multi-energy source capacity constraints and electrical constraints are taken as the constraints. Based on the complex adaptive system theory, the minimum construction step size of new energy sources is taken as the agent for modeling, focusing on the coordination among multiple sources, adjusting the installed node position and capacities of various types of power sources to obtain the optimal layout of power sources for multi-energy power systems. Based on the actual meteorological and operational data of a regional power grid in Northwest China, the original power system is re-planned. The simulation results verify the effectiveness of the proposed planning method.

INDEX TERMS Agent modeling, complementarity, complex adaptive system, multi-energy power system, power planning.

I. INTRODUCTION

In order to cope with the shortage of fossil fuels, the aggravation of environmental pollution and global climate change and other important issues, vigorously developing non-fossil energy, especially new energy represented by wind and solar energy, has become a universal choice for countries around the world to formulate energy policies and promote clean energy transition [1]. Photovoltaic power generation and wind power generation have little impact on the environment, have better long-term economics, so they are easier to be widely promoted and applied [2], [3]. However, the output power of individual photovoltaic power generation or wind power generation fluctuates greatly, which will cause impact on the grid during grid connected operation [4]–[6]. Since different energy forms have strong complementarity in time and region [7], making full use of the complementary characteristics of solar and wind energy and adopting multi-energy complementary power generation methods can enhance the reliability of system power supply, reduce the impact on the grid, improve the consumption of intermittent renewable energy in the grid, and achieve reasonable energy utilization effect and benefit [8].

The reasonable connection of new energy sources to the power grid plays an important role in improving voltage quality, reducing network loss, alleviating power stress, improving system reliability and reducing environmental pollution. However, when the new energy source is connected unreasonably, it will also have some adverse effects on the power system, such as harmonic pollution, voltage fluctuation and increased technical and economic risks [9]–[13]. Western China has abundant hydropower, solar and wind energy resources [14]. At present, many provincial and municipal power grids have formed a framework of wind-light-water-fire-storage complementary power supply, and the penetration rate of renewable energy is gradually increasing [15]. Application of multi-energy complementary renewable energy power generation system, while reducing the output fluctuation of a single station, is conducive to overcoming the waste of resources caused by the resource enrichment period of a single station [16]. In reference [1], a new generation planning method for large-scale grid connected new energy is proposed under the framework of investment decision-making and operation analysis. Considering

The associate editor coordinating the review of this manuscript and approving it for publication was S. Ali Arefifar.

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the seasonal fluctuation characteristics and rapid investment and construction characteristics of new energy, the power investment decision-making idea based on monthly investment time unit is proposed. In reference [8], a decision-making model for capacity planning of photovoltaic-wind power-energy storage hybrid power system is established based on game theory. Investors of wind power generation, photovoltaic power generation and energy storage battery are regarded as participants in the game, and the Nash equilibrium results of each mode are solved and compared with each other. Reference [17] applied the actual power grid of Israel to analyze the matching problem of large-scale wind power generation and photovoltaic power generation system. Through the comparison of wind and solar single and complementary operation modes, the wind and solar complementary configuration power generation mode was obtained, which improved the power penetration of intermittent energy to the grid. In order to realize the continuity and smoothness of power generation, the literature [18] defines the complementarity rate and smoothness index, studies the complementary optimization strategy of power generation resources with intermittent power sources, and proposes the allocation ratio of non-adjustable resource capacity and adjustable resource Quantitative analysis method of configuration capacity. Reference [19] proposed a capacity optimization allocation model of wind-solar hybrid power supply system based on improved differential evolution algorithm. On the premise of meeting the basic performance index of independent power supply system, the objective function with the minimum comprehensive cost of system investment cost, operation cost and maintenance of power supply reliability of the system as the objective is constructed. Due to the flfluctuated wind output power, the system parameter uncertainties and load disturbances, these may lead to the unstable operation of renewable energy power system for the larger voltage deviation. Therefore, paper [20] proposes a new design of adaptive model predictive control for energy conversion system with wind torque effect. Paper [21] presents a load frequency control (LFC) design using sliding mode technique in a multi-area power system inculding wind turbines. Paper [22] deals with the design of a new robust controller to solve automatic generation control (AGC) problems in interconnected multi-area power system using the metaheuristic Bat Inspired Algorithm (BA). In paper [23], control and operation of an isolated dc micro grid which consists of PV systems, wind turbines, energy storage and DC loads is investigated, which can reduce the impact on power system caused by the penetration of renewable energy systems.

The above literature studies the capacity allocation of new energy sources from the aspect of economic investment, and incorporates complementarity into the research scope, but the definition of complementarity is not uniform, and the research objects are mostly limited to wind power and photovoltaic power. Moreover, the current literature lacks in-depth analysis of the relationship between heterogeneous energy sources and the complexity of multi-energy power systems. Therefore, considering the output characteristics of wind power, photovoltaic, hydropower, thermal power and solar thermal power, based on the complex adaptive system theory, focusing on the complex coupling relationship between heterogeneous energy sources, this paper analyzes the complexity generation mechanism of multi-energy power system, and proposes a multi-point layout planning and design method of wide-area complementary new energy. The contributions of this paper are threefold as follows.

1) Analyse the complex coupling relationship between different areas and different types of power supplies. Taking the actual system as an example, under the condition that other power sources remain unchanged, the position and capacity of a wind turbine, are changed, and the new energy consumption data are calculated through production simulation. From the data, we can see the clear nonlinear characteristics of the multi-energy power system.

2) An agent-oriented modelling method is proposed. Regarding various types of regional power sources as agents, the interaction between the agents is used to characterize the complementary relationship between different power sources in the multi-energy power system so that the system can operate efficiently and stably.

3) Through the proposed model and solution method, various power supply multipoint layout schemes of the multi-energy power system can be obtained, and the installed type and capacity of each node can be determined. The utilization efficiency of new energy generating units has been significantly improved.

The remainder of this paper is organized as follows. Section II briefly introduces the theory of complex adaptive system. Section III analyses the complex coupling relationship in a multi-energy power system. Section IV illustrates the computation method. Section V validates the correctness and computation performance. Section VI provides the conclusion and future work.

II. COMPLEX ADAPTIVE SYSTEM THEORY

The complex adaptive system (CAS) was proposed by the Santa Fe Research Institute. The theory includes two aspects: micro and macro [24]. At the micro level, adaptive and active individuals are simply referred to as agents. An agent exhibits a certain adaptability in interaction with the environment; that is, to better survive in an objective environment, the behaviour rules can be modified according to the effects of the agent's behaviour. At the macro level, the system is composed of agents and develops with the interaction between agents and the environment, showing various complex evolution processes such as differentiation and emergence [25].

The multi-energy power system is composed of a variety of power generation forms. Various forms of power sources cooperate with each other and coordinate with each other in a more efficient and comprehensive way. In the multi-energy power system, different locations, different types and different capacities of power sources interact with each other.

The power sources are not simple, passive and unidirectional causality, but adaptive adaptation relationship. Most of the interactions are nonlinear, and the whole is not equal to the simple accumulation of each part. The output fluctuation of any power source will affect the output of other power sources. Each power supply adapts to each other and develops together in the nonlinear environment. Multi-energy power system is a typical complex adaptive system.

III. COMPLEXITY OF MULTI-ENERGY POWER SYSTEM

Taking the simplified power system of a province in China (Appendix Fig 8) as an example, the complex connection and nonlinear coupling relationship between power sources in a multi-energy power system are explained. There are two wind farms in the area, connected to the node 2 and node 15 respectively. The total installed capacity of the two wind farms is 2050MW. Under the condition that the total installed capacity of the two nodes is not greater than 2050MW and the installed capacity and location of other types of power sources remain unchanged, the installed capacity of wind power of the two nodes is redistributed. The annual consumption of new energy (wind power, photovoltaic, solar thermal) of the system is shown in Fig 1.

It can be seen from the figure that with the increase of the total installed capacity of wind power, the annual consumption of wind power also increases. However, when the total installed capacity of wind power is small (the total capacity is less than 500 MW), the annual photovoltaic consumption is significantly lower, and the amount of abandoned new energy power is relatively high. This shows that the connection of wind power has a certain promotion effect on the consumption of photovoltaic energy in the system. Moreover, due to the strong volatility and randomness of the new energy sources, when the peak load regulation capacity of the system is insufficient, a single form of new energy is not conducive to consumption.

The new energy consumption will be limited by the transmission section due to the different power access nodes. The new energy curtailment caused by transmission section constraints is shown in Fig 2. It can be seen from the figure that with the increase of the installed wind power capacity at node 2, the abandoned new energy power due to cross-section constraint also increases. The installed capacity of other types of power supply at node 2 is higher, resulting in the limitation of new energy transmission.

With the increase in the total installed capacity of wind power at two nodes, the annual consumption of new energy of the system also increases, shown in Fig 3. When the total installed capacity of wind power at two points is equal to 2050MW, the annual consumption of new energy reaches the maximum.

Under the condition that the total installed wind power capacity at the two nodes (2050 MW) remains unchanged, the new energy consumption is shown in Fig 4. It can be seen from the figure that the point with the largest annual consumption of wind power (node 15 wind power installed

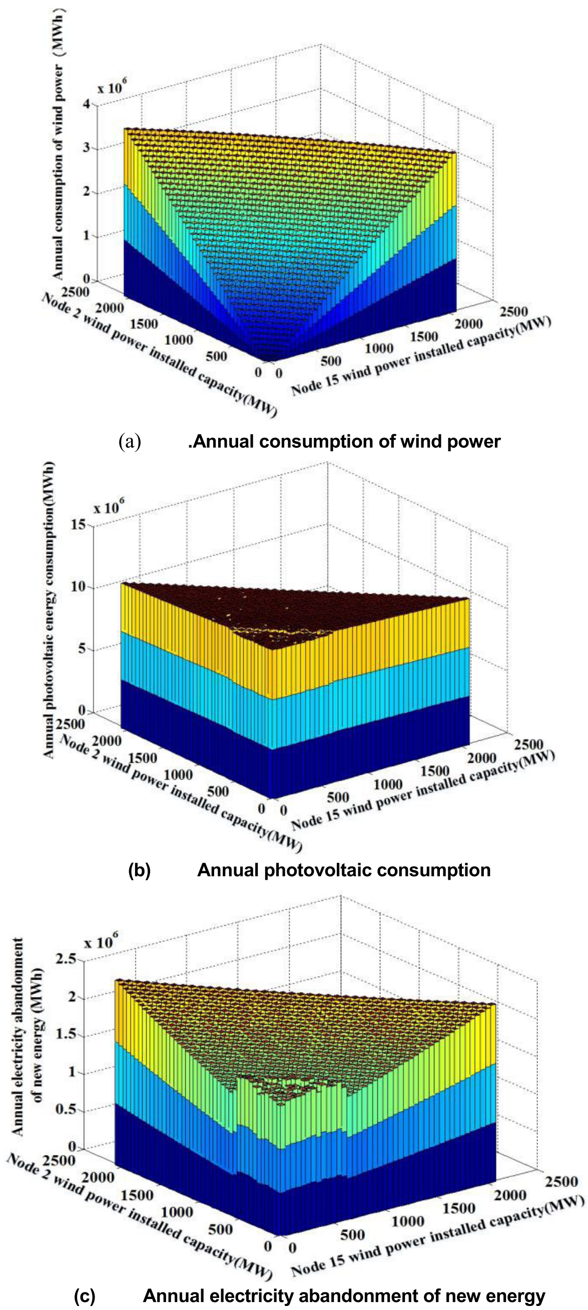

FIGURE 1. Annual consumption of new energy.

capacity is 1800 MW, node 2 wind power installed capacity 250 MW) is not consistent with the point with the largest annual consumption of new energy (node 15 wind power installed capacity is 1900 MW, node 2 wind power installed capacity is 150 MW).

From the above analysis, the complementary characteristics of various heterogeneous energies can promote the consumption of new energy in the system. Different access points have different natural resource conditions and grid section restriction thresholds. Even at the same installed capacity level, different wind turbine access nodes not only affect the

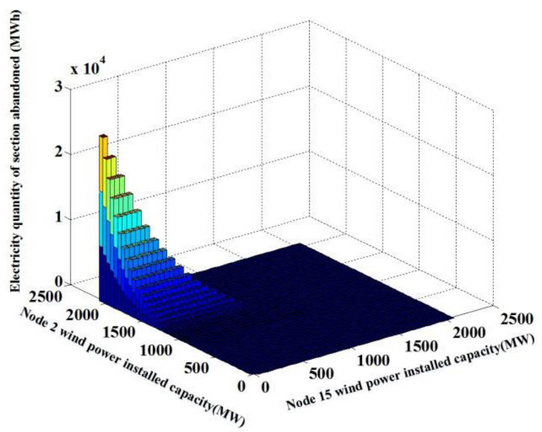

FIGURE 2. Annual section abandoned electricity of new energy.

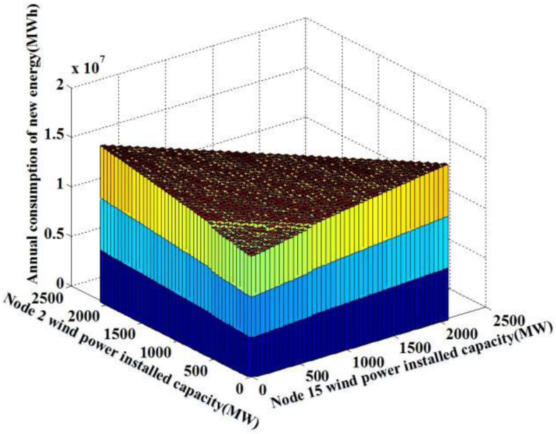

FIGURE 3. Annual consumption of new energy.

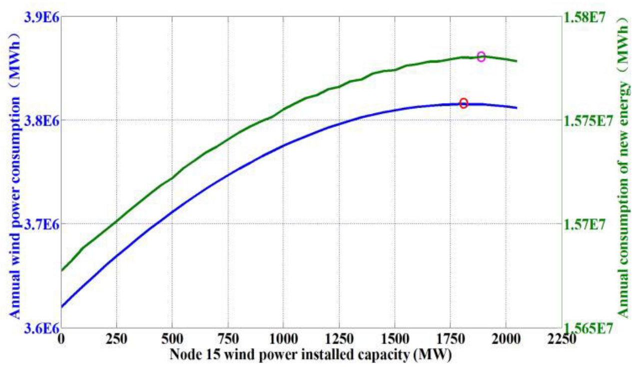

FIGURE 4. Change of annual consumption of new energy.

wind power consumption, but also affect the total new energy consumption. The coupling relationship between new energy sources has very complex nonlinear characteristics.

There is currently a lack of research on the inherent complexity of multi-energy power systems. A multi-energy power system cannot be understood correctly using simple addition of its constituent elements. Instead, the complexity of the system must be reproduced with an indivisible overall view, an interconnected organic view, and a dynamic view of each element. This paper focuses on the relationship between new energy sources, combined with CAS theory, and proposes a multi-energy power system power planning model based on agent modeling, which provides a new idea and method for power planning theory.

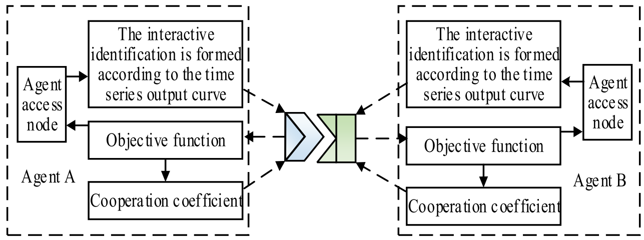

FIGURE 5. Model structure.

IV. PLANNING MODEL

Five types of power sources are selected: wind power, photovoltaic, hydropower, thermal power and solar thermal power. Since thermal power and hydropower units are installed at relatively fixed locations and new energy power installations are relatively flexible, the minimum construction step size of each type of new energy sources is taken as the agent, and the total installed capacity is discretized and modeled in the way of facing the agent.

A. AGENT MODEL

The agents select each other according to the identification, and then participate in the evolution iteration process as a whole after aggregation. The objective function determines the access node of the agent source. Through the interaction between agents and accumulation of experience, the cooperation coefficient and access nodes are continuously changed, and the installed capacity of each type and node power supply is adjusted, and finally the stable state is maintained, so as to obtain the optimal layout scheme of various power capacity of each node. The agent structure is shown in Fig 5.

1) IDENTIFICATION MECHANISM

In CAS, identity is a mechanism that exists behind agents in order to identify each other and select aggregation. In the process of agent interaction, identification is an important guiding mechanism, through which the agent selects the interactive object in the system. By identifying the characteristics of each agent, the interaction between agents can be effectively promoted. In the process of interaction, the agent will produce new identification, which provides the possibility of further coupling and aggregation.

For the multi-energy power system, the identification of different types of power sources is their sequential output characteristics. For example, wind power output is "low at noon and high at night," while photovoltaic output is "high at noon and low at night." Differentiation oriented identification plays an important role in the complementary and coordinated development of multi-energy power system. In the interaction process of each power supply agent, due to the consistency of objectives, cooperative behavior will occur, which is reflected in complementarity. Due to the characteristics of real-time source load balance in power system, this paper defines complementarity as the closeness between power output and load curve in time scale.

Based on the above analysis, the statistical output characteristics of all types of power sources at 24 hours in a year constitute the feature tag sequence:

$$\Psi_k = \left[\varphi_{1,n}^k, \varphi_{2,n}^k \cdots \varphi_{24,n}^k\right] \tag{1}$$

Ψ_k is the tag sequence of the n iteration of the agent k. Where:

$$\varphi_{i,n}^k = \frac{\sum_{t=1}^{8760} P_{t,n}^k}{\max(\sum_{t=1}^{8760} P_{t,n}^k)} \quad \begin{cases} t = d^*24 + i \\ d = 0, 1 \cdots 364 \end{cases} \tag{2}$$

where $p_{t,n}^k$ is the actual output at time t of the n iteration of the agent k. $\max(\sum_{t=1}^{8760} P_{t,n}^k)$ is the maximum absorption value of k agent statistics in 24 hours. The sequence of agent feature identification is a real number between [0, 1].

The tag of an agent is related to its timing output characteristics. This value represents the characteristics of the agent, such as wind power output characteristics that are high at night and low at noon, and photovoltaic output characteristics that are high at noon and low at night. Due to the difference of the agent's location, node and natural resources of an agent, with the development of the evolution process, the time series output of the agent will also change through the calculation of sequential production simulation. Therefore, the tags of agents under different spatiotemporal conditions have the characteristics of time-variability and diversity, which provide data basis for the diverse cooperation among the agents.

Similar to the tag process of the agent, the load tag is established ($\Psi_{load} = \left[\varphi_1^{load}, \varphi_2^{load} \cdots \varphi_{24}^{load}\right]$). Since the load does not change in the planning level year, its tag array is relatively fixed. The matching degree can be obtained by comparing the tags of the agent and load:

$$\eta_n^{k,load} = \sum_{j=1}^{24} \left|\varphi_{j,n}^k - \varphi_j^{load}\right| \tag{3}$$

where $\eta_n^{k,load}$ is the matching degree between the agent k and the load in the iteration n.

2) AGGREGATION MECHANISM

The analysis in Section III shows that the coupling relationship between new energy sources has very complex nonlinear characteristics. The agent of power supply gathers in accordance with the development trend of the system, which produces nonlinear amplification effect and enhances the adaptability of the original agent. In the process of selective interaction, each agent changes the position of the access node, and the output curve and the value of the objective function also change, and then a new identification is generated. Moreover, the completion of each adaptation process opens up new possibilities for the next adaptation, so as to maintain the continuous updating of multi-energy power system and promote the deeper aggregation of each agent.

It can be seen from the above formula that the smaller the matching degree is, the smaller the volatility is, that is, the better the complementarity is. The cooperation mechanism among agents is determined as follows:

$$\begin{cases} \eta_n^{k,load} \geq \eta_n^{k,l,load} \\ \eta_n^{l,load} \geq \eta_n^{k,l,load} \end{cases} \tag{4}$$

where $\eta_n^{k,l,load}$ is the matching degree of combined output and load of the agent k and the agent l. If $\begin{cases} \eta_n^{k,load} \geq \eta_n^{k,l,load} \\ \eta_n^{l,load} \leq \eta_n^{k,l,load} \end{cases}$ or $\begin{cases} \eta_n^{k,load} \leq \eta_n^{k,l,load} \\ \eta_n^{l,load} \geq \eta_n^{k,l,load} \end{cases}$ is satisfied, the agent k and the agent l cooperate with each other with a certain probability of forming a unified agent. In addition, when an agent's consumption decreases, if the other agent's consumption increases and the increase value is greater than the decrease value, the two agents will also aggregate.

At the micro level, the two agents gather to form a unified agent; from the macro level, the new energy sources are complementary and coordinated. The form of the agent can be expressed as:

$$H = \sum_{m_{\text{type}}} \sum_{i=1}^{n} h_{m_{\text{type}},i} \tag{5}$$

where H is the aggregate generated by the aggregation of multiple agents, m_{type} is the power type of the agent, and i is the agent number.

B. OBJECTIVE FUNCTION

Each agent takes the maximum consumption of new energy as the objective function:

$$\max Q_H = \sum_{m_{\text{type}}} \sum_{i=1}^{n} Q_{h_{m_{\text{type}},i}} \tag{6}$$

where Q_H is the annual consumption of new energy of aggregate H; $Q_{h_{m_{\text{type}},i}}$ is the annual consumption of new energy of agent $h_{m_{\text{type}},i}$ contained in aggregate H.

Analyzing the models in section A, it can be seen that each agent connects with the other agents through the identification mechanism, establishes the cooperation and aggregation relationship, and determines the access node with the goal of maximizing the consumption of new energy. Due to the nonlinear relationship between the agents, when the position of any agent changes, it will not only affect the current agent output, but also affect the output of other agent. As all agents choose the node location with the same goal, the new energy consumption of the whole system gradually increases, and finally converges dynamically to the maximum value.

TABLE 1. Planning scheme.

Node Number	Wind Power (MW)	Photo Voltaic (MW)	Hydro Power (MW)	Thermal Power (MW)
0	2150	1500	1280	870
1	850	0	0	0
2	150	500	1390	270
3	0	150	1450	960
4	0	1650	1533	970
7	0	0	0	1570
8	0	50	0	660
10	0	0	0	700
13	0	0	0	8050
14	0	0	0	1400
18	0	350	685.5	2460
19	0	200	0	5240
20	0	200	0	5870
21	4250	0	0	0
22	1250	700	810	1800
23	0	150	0	250
24	50	350	0	1400
25	300	250	0	0
26	400	950	0	1980
27	0	450	0	1360
29	0	0	0	5280
30	3850	0	0	0
31	800	1650	0	930
32	1050	50	0	660
34	0	350	0	1280
35	4950	850	0	0
36	700	0	0	6405

C. CONSTRAINTS

1) POWER FLOW CONSTRAINT

To simplify the calculation, the DC power flow calculation method is adopted:

$$P = B\theta \tag{7}$$

where P is the column vector of active power injected into a node. B is the node admittance matrix. θ is the phase angle column vector of node voltage.

2) CLIMBING CONSTRAINTS

$$\begin{cases} \Delta P_{i,up}^{t} \leq P_{i,the,\max up}^{t} + P_{i,hyd,\max up}^{t} + P_{i,stp,\max up}^{t} \\ \Delta P_{i,up}^{t+1} \leq P_{i,the,\max up}^{t+1} + P_{i,hyd,\max up}^{t+1} + P_{i,stp,\max up}^{t+1} \end{cases} \tag{8}$$

where $\Delta P_{i,up}^{t}$ is the climbing power of node i at time t. $P_{i,the,\max up}^{t}$, $P_{i,hyd,\max up}^{t}$, $P_{i,stp,\max up}^{t}$ are the maximum climbing power of thermal power, hydropower and solar thermal power, respectively, of node i at time t.

$$\begin{cases} \Delta P_{i,down}^{t} \leq P_{i,the,\max down}^{t} + P_{i,hyd,\max down}^{t} \\ \qquad + P_{i,stp,\max down}^{t} \\ \Delta P_{i,down}^{t+1} \leq P_{i,the,\max down}^{t+1} + P_{i,hyd,\max downp}^{t+1} \\ \qquad + P_{i,stp,\max down}^{t+1} \end{cases} \tag{9}$$

TABLE 2. Simulated calculation data.

Indexes	Original scheme	Planning scheme
Wind power/GWh	91874.2	94689.9
Photovoltaic power/GWh	15061.5	15100.1
Hydropower /GWh	28285.5	28191.3
Thermal power/GWh	259210.2	256496.5
Abandoned wind power/GWh	18522.4	17892.4
Abandoned photovoltaic power/GWh	1876	2061.2
Abandoned Hydropower/GWh	1703.1	1811
New energy abandonment/GWh	20398.3	19953.5
Wind abandonment rate/%	16.778	15.892
photovoltaic abandonment rate/%	11.076	12.01
Hydropower abandonment rate/%	5.679	6.036
Electricity abandonment rate of new energy/%	16.02	15.379

where $\Delta P_{i,down}^{t}$ is the downhill power of node i at time t. $P_{i,the,\mathrm{maxdown}}^{t}$, $P_{i,hyd,\mathrm{maxdown}}^{t}$, $P_{i,stp,\mathrm{maxdown}}^{t}$ are the maximum downhill power of thermal power, hydropower and solar thermal power of node i at time t.

3) CAPACITY CONSTRAINTS

$$\sum_{i=1}^{N} C_{type,new}^{i,y} = C_{type,plan}^{y} \tag{10}$$

where $C_{type,new}^{i,y}$ is the new type power capacity of node i in year y; N is the total number of nodes, and $C_{type,plan}^{y}$ is the total capacity of the *type* power supply planned to be added in year y.

4) SECTION CONSTRAINT

$$\sum_{m=1}^{n} P_{i,m} \leq P_{i,\sec tion,\max} \tag{11}$$

where $P_{i,l}$ is the transmission power of line m in the section of node i; $P_{i,\sec tion,\max}$ is the maximum transmission power of node i.

D. POWER OUTPUT MODEL

The output power of the turbine is closely related to the wind speed. The wind speed generally follows the Weibull distribution, and its probability density function is expressed as follows:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{12}$$

where v is the real-time wind speed; k, c are the shape parameters and scale parameters respectively. The relationship between the turbine output power $P_{win,t}$ and wind speed is as follows:

$$P_{win,t} = \begin{cases} 0 & v \leq v_{ci},\ v > v_{co} \\ \dfrac{v - v_{ci}}{v_N - v_{ci}} P_{win,N} & v_{ci} < v \leq v_N \\ P_{win,N} & v_N < v \leq v_{co} \end{cases} \tag{13}$$

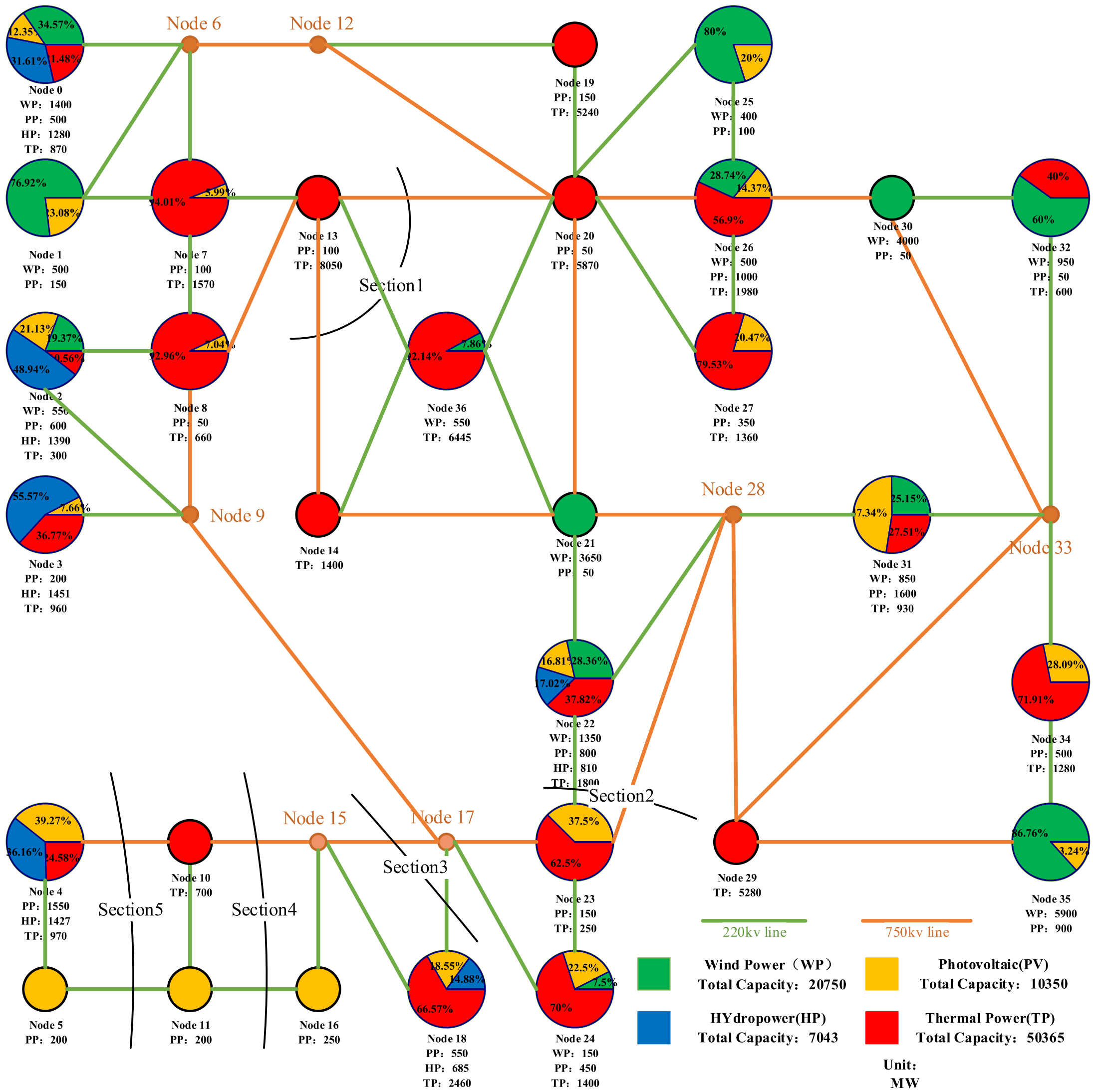

FIGURE 6. Structural diagram of multi-energy power system.

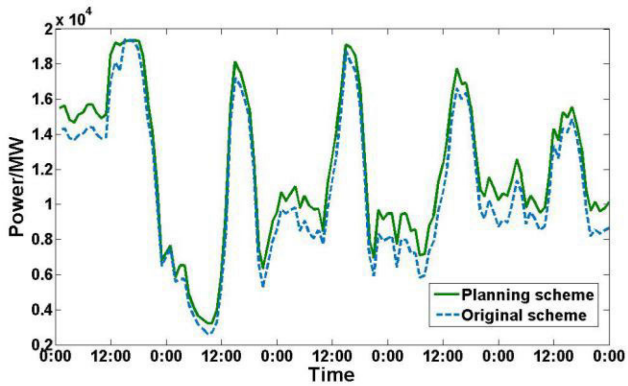

FIGURE 7. New energy consumption time series diagram.

where $P_{win,N}$ is the rated power of the turbine; v_{ci}, v_{co}, v_N are the cut in wind speed, cut-out wind speed and rated wind speed of the turbine respectively.

The light intensity γ obeys a Beta distribution in a certain period, the probability density function $f(\gamma)$ is:

$$f(\gamma) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\gamma^{\alpha-1}(1-\gamma)^{\beta-1} \tag{14}$$

where α, β are the shape parameters and $\Gamma()$ is the Gamma function. The relationship between photovoltaic power $P_{pv,t}$ and light intensity is as follows:

$$P_{pv,t} = \begin{cases} P_{\mathrm{PV,N}} & \gamma > \gamma_{\mathrm{N}} \\ P_{\mathrm{PV,N}}\dfrac{\gamma}{\gamma_{\mathrm{N}}} & \gamma \le \gamma_{\mathrm{N}} \end{cases} \tag{15}$$

where $P_{\mathrm{PV,N}}$ and γ_{N} are the rated power and rated light intensity of photovoltaic power respectively.

The output power of hydropower $P_{hyd,t}$ meets the following constraints:

$$\begin{cases} P_{hyd,\min} \le P_{hyd,t} \le P_{hyd,\max} \\ P_{hyd,down} \le P_{hyd,down\max} \\ P_{hyd,up} \le P_{hyd,up\max} \end{cases} \tag{16}$$

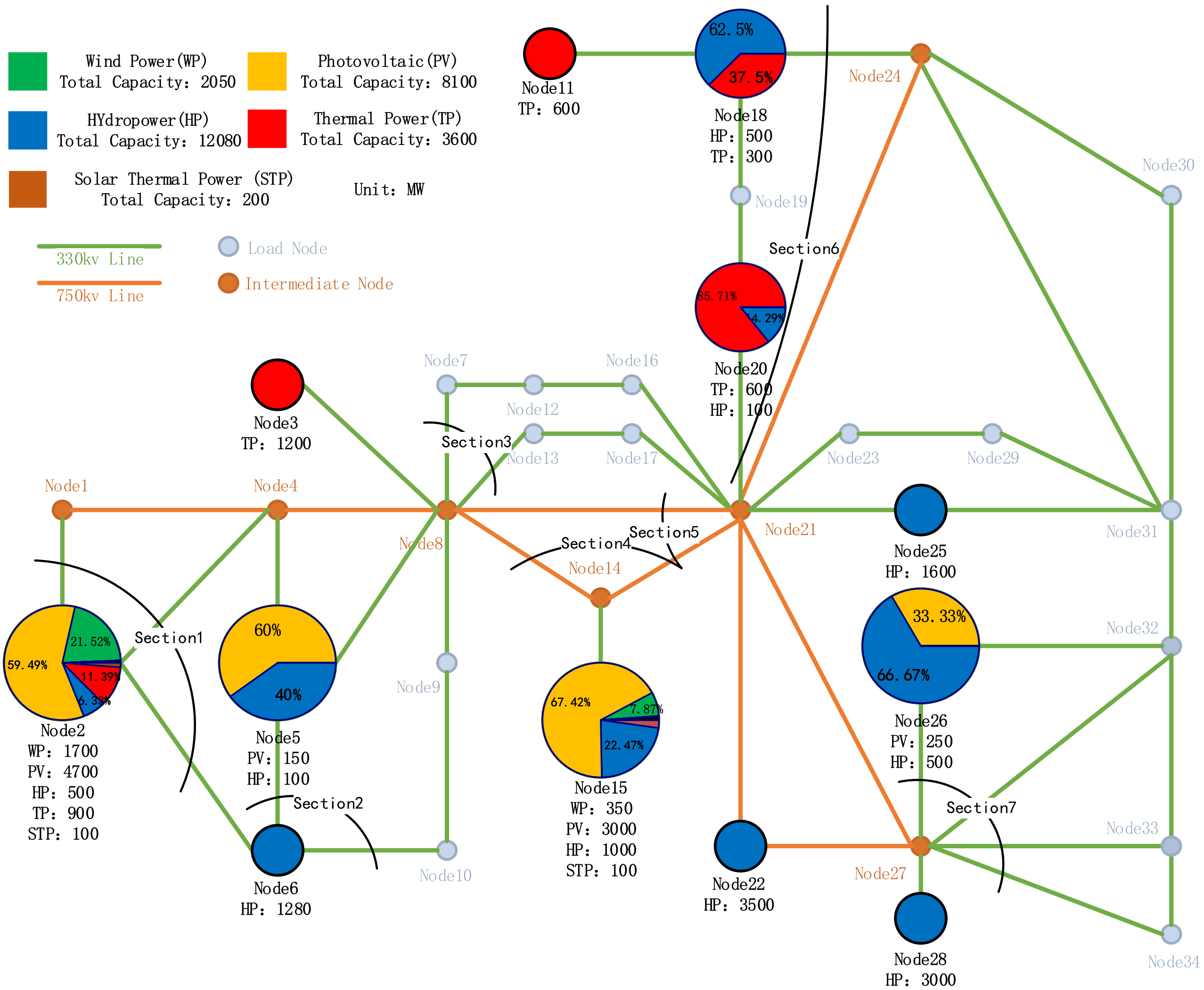

FIGURE 8. Power system structure diagram.

where $P_{hyd,\min}$ and $P_{hyd,\max}$ are the minimum and maximum output power of the hydropower plant; $P_{hyd,up}$ and $P_{hyd,down}$ are the climbing and downhill power of the hydropower plant; $P_{hyd,up\max}$, $P_{hyd,down\max}$ are the maximum climbing and downhill power of the hydropower plant.

The output power of thermal power $P_{the,t}$ meets the following constraints:

$$\begin{cases} P_{the,\min} \leq P_{the,t} \leq P_{the,\max} \\ P_{the,down} \leq P_{the,down\max} \\ P_{the,up} \leq P_{the,up\max} \end{cases} \tag{17}$$

where $P_{the,\min}$ and $P_{the,\max}$ are the minimum and maximum output power of thermal power plant; $P_{the,up}$ and $P_{the,down}$ are the climbing and downhill power of thermal power plant; $P_{the,up\max}$ and $P_{the,down\max}$ are the maximum climbing and downhill power of thermal power plant.

The relationship between the output power of solar thermal power $P_{stp,t}$ and light intensity is as follows:

$$P_{stp,t} = \begin{cases} \eta_{p,e} P_{stp,N} & \gamma > \gamma_N \\ \eta_{p,e} P_{stp,N} \dfrac{\gamma}{\gamma_N} & \gamma \leq \gamma_N \end{cases} \tag{18}$$

Solar thermal power stations generate electricity through steam turbine units, so they have operation constraints similar to those of conventional steam turbine units. In addition, the charging/discharging power of the energy storage tank of a photothermal power station can be continuously adjusted within a limited range, but charging/discharging cannot be carried out simultaneously.

$$\begin{cases} 0 \leq P_{stp,sto,in} = \eta_{p,h} P_{stp,N} \dfrac{\gamma}{\gamma_N} \leq P_{hea,sto,in}^{\max} \\ 0 \leq P_{stp,sto,out} = \eta_{h,e} P_{stp,N} \dfrac{\gamma}{\gamma_N} \leq P_{hea,sto,out}^{\max} \\ P_{stp,sto,out} \times P_{stp,sto,in} = 0 \end{cases} \tag{19}$$

where $P_{stp,N}$ and γ_N are rated power and rated light intensity of the photovoltaics, respectively. $P_{stp,sto,in}^{\max}$ and $P_{stp,sto,out}^{\max}$ are

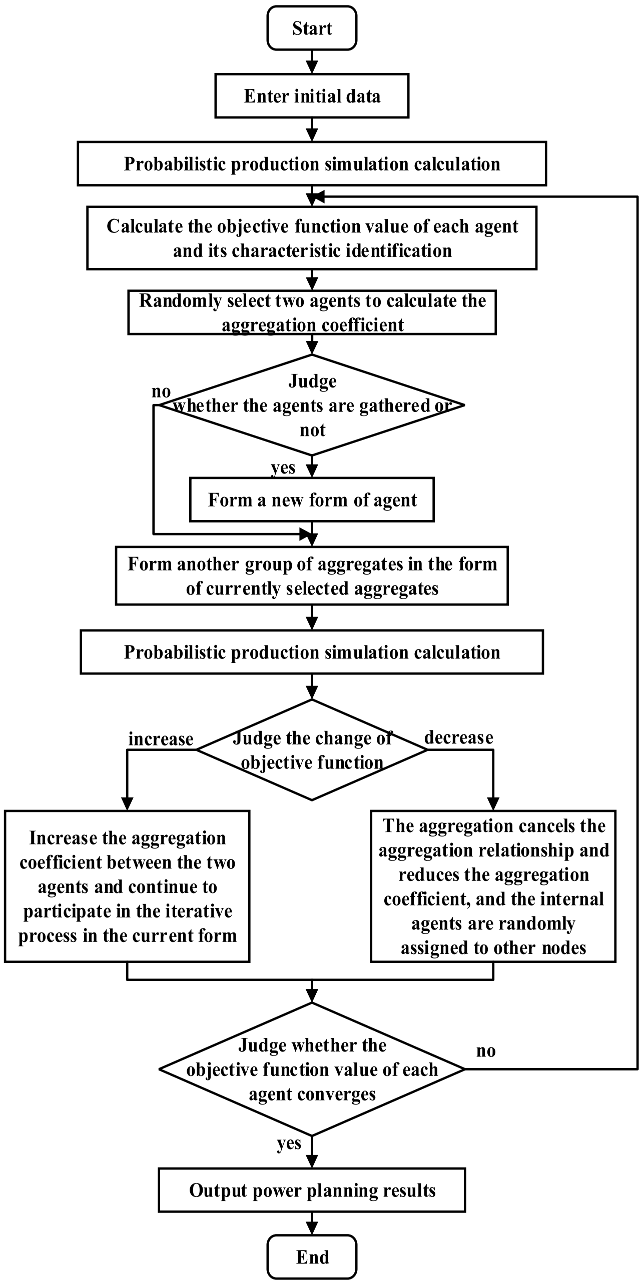

FIGURE 9. Flow chart.

the maximum charging and discharging power. $\eta_{p,h}$, $\eta_{h,e}$, $\eta_{p,e}$ are photothermal, thermoelectric and photoelectric conversion efficiencies, respectively.

E. MODEL SOLVING

1) Enter the initial data, including the initial installed capacity of each type of power supply and the annual natural resources and load values of each node.
2) Combined with CAS theory, the smallest construction unit of new energy power supply is selected as the agent. Initialize the object function value and feature identification sequence of the agent.
3) Carry out stochastic production simulation calculation in consideration of wind and solar volatility, and obtain the consumption value of each agent and its characteristic identification sequence. Two groups of agents are randomly selected, and if the two agents meet the aggregation conditions, they are gathered.
4) If the new energy consumption of the system increases, the aggregation coefficient between the two agents will increase, and continue to participate in the iterative process in the current form. Otherwise, the two groups of aggregates cancel the aggregation relationship and reduce the aggregation coefficient, and the internal agents are randomly assigned to other nodes.
5) Judge whether the power capacity of each node in the system converges. If converged, output the planning plan, otherwise go to step 3) for iterative calculation. The specific process is shown in Fig 9 in the Appendix.

V. EXAMPLE ANALYSIS

Taking the actual power system of a province in Northwest China as an example, the power layout optimization simulation is carried out. The original structure of the system is shown in Fig 6, and five sections are divided according to the actual operation. In the case of the same load level and the total capacity of various power sources unchanged, the method proposed in this paper is used to re-layout and calculate the specific distribution of various power sources. The optimal planning scheme is shown in Table 1, and the calculation data of stochastic production simulation is shown in Table 2.

It can be seen from Table 2 that after the proposed method is used to re-layout the power sources, the installed capacity of severely restricted sections will decrease, and the installed capacity of new energy will increase in areas rich in natural resources. In terms of electricity consumption, the output of thermal power has been greatly reduced, and the consumption of new energy has been significantly increased, reducing the phenomenon of new energy curtailment. Renewable energy output can replace part of thermal power generation, which helps to reduce fuel consumption and carbon emissions, and improve economic and environmental benefits.

The optimization of planning scheme is not only reflected in the new energy consumption, but also reflected in the volatility of new energy output. Five days of new energy output in one year is randomly selected for comparison, as shown in Fig 7.

In the optimal planning scheme, the fluctuation of the sum of new energy output power of the system is reduced, which is because in the optimization process, the relationship between the agents is emphasized, the time series output characteristics are taken as the interactive identification, and the minimum volatility compared with the load is the aggregation standard. Moreover, the agent is always in the process of development, decline and mutation, and changes its structure and behavior mode to maintain its survival and development. As the system evolves, the agent will be more robust, reliable and diverse, so that it can adapt to a wider range of environmental conditions, lead the evolution of the system, make full use of the complementary characteristics of new energy, maximize the rational utilization of renewable resources, effectively smooth the fluctuation of renewable energy, ensure the continuity and smoothness of power generation, and make the multi-energy operate economically and reliably.

VI. CONCLUSION

The adaptation process of a CAS is essentially a dynamic and generalized optimization evolution process that is based on the group. Due to the existence of mutual adaptation and mutual influence, the parts that make up the whole are not equal to simple linear accumulation, and attention must be paid to the emergence of structure and function from the bottom up at the system level brought about by the combination of elements. CAS theory provides good theoretical support for the study of dynamic, nonlinear and uncertain problems and can also be seen as a new method that replaces the traditional derivation-analysis method.

In view of the current situation and future development trend of large-scale multi-energy power system, this paper studies the output complementarity of wind power, photovoltaic power, hydropower, thermal power and photothermal power, analyzes the complex coupling relationship between new energy sources, and proposes a multi-point layout planning model of new energy sources based on complex adaptive system theory. The main conclusions are as follows:

1) Analyze the characteristics of the multi-energy power system based on the theory of complex adaptive systems, and propose a multi-type power multi-point layout planning method.

2) Based on the analysis of complementarity and volatility, a multi-point layout planning model of multi-energy power system with the maximum new energy consumption as the goal is established, which can effectively enhance the new energy consumption, reduce the emission of conventional units, improve the investment economy of new energy sources and reduce environmental pollution.

3) The optimal scheme obtained from the model can guide decision-makers to determine the final planning scheme, which has a certain reference value for the multi-point layout planning of multi-energy power system.

In the situation of large-scale integration of new energy, the power planning problem with new energy has always been the research focus in this field. In the future research, the following key issues should be paid attention to.

1) This paper focuses on the power supply planning, and considers that the grid structure remains unchanged. In the next research, we can consider the changes of the power grid and carry out the coordinated planning of the power grid.

2) At present, reinforcement learning technology is seeking to improve the existing planning model. In future research, reinforcement learning technology can be combined with the planning model proposed in this paper.

3) Complex adaptive system is very suitable for the study of system evolution. In the follow-up research, we can combine the theory of complex adaptive system to study the evolution process of power system.

APPENDIX

See Figures 8 and 9.

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