Innovative Design and Intelligent Manufacturing L.C. Jain et al. (Eds.) © 2024 The Authors. This article is published online with Open Access by IOS Press and distributed under the terms of the Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC 4.0). doi:10.3233/FAIA241144

Novel Power System Design and Optimization Based on Renewable Energy Integration

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Abstract. This study introduces an optimized power system design that integrates renewable energy, focusing on sustainable development and economic efficiency. Using particle swarm optimization, the capacity allocation model shows that optimizing wind turbine models can increase resource utilization and reduce costs. The final system includes 500 wind turbines (750MW), PV modules (300MW), and generators (1050MW total) with 3500MWh storage, achieving a total capacity of 1550MW. The results confirm the method's effectiveness in reducing emissions and enhancing system performance.

Keywords. new power system; integrated energy system; capacity allocation; particle swarm algorithm

1. Introduction

Energy is the prerequisite and guarantee for human survival and healthy social development. At present, China is in a period of rapid development of urbanization and industrialization, and the energy demand is increasing dramatically [1-3]. In addition, the traditional energy system of large capacity, high parameters, centralized power generation mode, is not conducive to intermittent, fluctuating and stochastic characteristics of renewable energy system access, resulting in abandonment of light, abandonment of wind phenomenon is very serious [4-7]. Therefore, to change the traditional energy utilization mode, to build a green, clean, low-carbon, efficient energy utilization form has become an inevitable choice to deal with the energy crisis and environmental problems.

Integrated Energy System (IES), as an advanced energy utilization technology, can make up for the shortcomings of traditional energy systems. The comprehensive energy system refers to the overall planning, design, construction and operation stages, and the organic

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coordination of the whole cycle of energy production, transmission, conversion, storage and consumption to achieve the integration of production, supply and consumption of multiple types of energy. The integrated energy system optimizes and integrates various forms of energy, such as heat, electricity and natural gas, through the overall scheduling of sources, networks, loads and storage, so as to realize the coupling, coordination, complementarity and cascade efficient utilization of all types of energy, and meet the diversified energy demand of users [8-9]. In addition, the integrated energy system can absorb renewable energy on a large scale, improve the schedulability of non fossil energy, effectively solve the mismatch problem in multiple space-time scales of the source and the load side in the process of complementary energy supply of multiple types of energy, thus significantly improving the overall energy efficiency of the system. Therefore, the integrated energy system has the characteristics of high efficiency, environmental protection, economy, reliability and flexibility, and is an effective way to achieve clean, low-carbon, safe and efficient energy supply [11].

2 The research methodology

2.1 Capacity Allocation Model

2.1.1 Establishment of constraints

The stored energy range constraints, charging and discharging power constraints, and power constraints of coal-fired generating units of the energy storage system have been reflected in the power model formulation. What also needs to be considered are the system constraints, including the system power supply deficit rate constraint, the energy waste rate constraint, and the energy supply deficit rate constraint.

(1) The system power supply deficit rate constraint defines the system annual power supply deficit rate (LPSP) is a measure of the size of the active power supply deficit of the energy generation system, which is the ratio of the total active power deficit of the system that fails to satisfy the load to the size of the total load at a typical time. The calculation formula is as follows:

$$LPSP = \sum_{t=1}^{n} max[P_L(t) - P_S(t), 0] / \sum_{t=1}^{n} P_L$$
(1)

where LPSP is the system power supply deficit rate; N is the number of divisible unit steps in a typical year. When PL (t) is the total load of the system at time t, PS (t) is the output power of the system grid at time t. The system power supply deficit rate is constrained as equation (2):

$$LPSP \le LPSP_{set}$$
 (2)

where LPSP_{set} is the maximum power supply deficit rate allowed for this system.

(2) The system energy waste rate constraint defines the system energy waste rate (SPSP), which is an indicator of the amount of energy supplied by the energy generation system in excess of the load, and is the ratio of the amount of energy supplied by the system power generation system in excess of the load to the total load in a typical time. It corresponds to the constraint of system power supply deficit rate, jointly constraining the range of PS fluctuation in the upper and lower limits of PL. As shown in equation (3) below.

$$SPSP = \sum_{t=1}^{n} max[P_{S}(t) - P_{L}(t), 0] / \sum_{t=1}^{n} P_{L}(t)$$
(3)

In the formula, the SPSP is the system energy waste rate. The system energy wastage rate is constrained as follows in equation (4): , the

$$\max_{n} f(n) = \sum_{i=1}^{n} n_i \tag{4}$$

Where, SPSPset is the maximum energy waste rate allowed by the system.

(3) System power supply loss rate constraint definition System power supply loss rate (LLP) is an indicator to measure the duration of the guaranteed load of the integrated energy generation system, and it is the ratio of the total time of the system with power failure areas to the power supply time in a typical time. Its definition is as follows:

$$LLP = \sum_{t=1}^{n} [i(t)]/n$$

$$i(t) = \begin{cases} 1, P_{S}(t) < P_{L}(t) \\ 0, P_{S}(t) \ge P_{L}(t) \end{cases}$$
(5)

In the formula, the LLP is the system power supply missing rate. The system power supply missing rate is constrained as follows in Eq. (6):

$$LLP \le LLP_{\text{set}} \tag{6}$$

In the formula, the LLP_{set} is the maximum supply default rate allowed by the system. (4) Power system tidal current constraints define the calculation of the state of the power system during steady state operation under normal and fault conditions, which is to find the distribution of voltage and power of the power system under a given mode of operation. The active and reactive power of all power nodes must be satisfied. The following equation (7).

$$P_{Gmin} \le P_{Gi} \le P_{Gmax}, Q_{Gmin} \le Q_{Gi} \le Q_{Gmax} \tag{7}$$

Among them, the upper and lower limits of Pand Q need to be determined with reference to the generation operating limits.

2.1.2 Establishment of the objective function

The objective of the optimized design of a power generation system at a site is to minimize the net present value of the cost of the main input equipment. The main input equipment consists of wind turbines, photovoltaic (PV) modules, power storage equipment, and coal-fired generators. The input cost of wind turbine includes the net present value of the initial acquisition cost and maintenance cost of the equipment, the input cost of photovoltaic module includes the net present value of the initial acquisition cost, maintenance cost of power storage equipment, and the input cost of coal-fired generator includes the net present value of the initial acquisition cost, maintenance cost and replacement cost of the equipment, and the input cost of coal-fired generator includes the net present value of the initial acquisition cost, maintenance cost of the equipment. The specific objective function is given in equation (8) as follows: ,

$$NPV = NPVw + NPVp + NPV_h + NPV_c$$
(8)

where NPV, NPVw, NPVp, NPV_h and NPV_c are the net present value of the total investment in major equipment and the net present value of the investment in wind turbines, photovoltaic modules, electric hydrogen storage equipment and coal-fired generating sets (unit: ten thousand yuan). The depreciation rate for this type of investment project is 5%. The project's life cycle of the main equipment input cash outflow diagram.

2.2 Preliminary selection and parameterization of equipment

The destination of the system is characterized by abundant scenery resources, cold weather, high altitude, weak ecosystem, and winter load greater than summer load. The service life of the system is 20 years. The climate in this region is colder than that in other regions. The winter is long. The annual average temperature is - $3.6 \,^{\circ}$ C, the average maximum temperature is $23 \,^{\circ}$ C, the average minimum temperature is - $3.6 \,^{\circ}$ C, the average maximum temperature is $23 \,^{\circ}$ C, the average minimum temperature is - $3.3 \,^{\circ}$ C, and the regional altitude is about 1500 meters. The annual average wind speed at 80m height of wind energy resources is 7.1m/s, the air density is $1.12 \,^{\circ}$ Mg and the average daily solar radiation of 1 square meter is about $3.2 \,^{\circ}$ Wh to $5.5 \,^{\circ}$ Wh. The characteristics of the system are that the load in winter is obviously greater than that in summer, and the peak load is obviously greater than the valley load. Taking the selected typical winter days as an example, the average wind speed is $6.4 \,^{\circ}$, the average temperature is - $11.4 \,^{\circ}$ C, and the solar radiation throughout the day is $4.9 \,^{\circ}$ Wh/m². The maximum load is 1178MW, and the minimum load is 728MW.

(1) The rated power of a single set is 1.5MW, the power regulation mode is variable pitch and variable speed regulation, the impeller diameter is 93m, the hub height is 75m, the cut in wind speed is 2.5m/s, the cut out wind speed is 19m/s, the rated wind speed is 9.5m/s, and the limit wind speed is 52.5m/s. The unit price is 3500 yuan/kW. The standby selection is for GW87/1500-75m direct drive high-altitude fan with slightly higher wind speed. This model has a single rated power of 1500kW. The power regulation mode is variable pitch variable speed regulation. The impeller diameter is 87m, the hub height is 75m, the cut in wind speed is 3m/s, the cut out wind speed is 22m/s, the rated wind speed

is 9.9m/s, and the unit price is 3400 yuan/kW. This model has high cut in wind speed and rated wind speed, and its advantage is low unit price.

Due to the low air density of the project and the fact that the PV modules are not affected by the air density, and the wind resource conditions are good, the WTGs have a high output situation, and a larger number of turbine arrangements would be the optimal choice. Considering the higher reliability of WTGs, better complementarity with PV modules, and the need to fully utilize the wind resources of the project site, 8 to 12 locations are finally selected for selection.

(2) With the development of the domestic photovoltaic market, the price of domestic single crystal silicon modules is almost the same as that of polycrystalline silicon modules. Combined with the current industrial status and production capacity of the domestic PV module market, the mainstream PV modules in the current market basically choose single crystal silicon modules with higher photoelectric conversion efficiency. The project initially selects a single 305Wp monocrystalline silicon photovoltaic module, and the unit array capacity is temporarily set as 500kWp for subsequent calculation. The unit array capacity is 0.5 MWp temporarily. Under standard test conditions, the single chip peak power is 305Wp, the open circuit voltage is 40.3V, the short circuit current is 9.83A, the nominal operating temperature is 45 °C, the operating temperature range is -40 °C to 85 °C, and the size of the battery module is 1650mm 992mm 35mm. The unit price is 0.96 yuan/Wp.

(3) Each energy storage system unit is preliminarily selected for the electric hydrogen production plant, and 550MW/3500MWh, that is, 6.3h charging and discharging are completed.

(4) The rated power of a single coal-fired power plant is 500MW, and the coal price of the project site is 520 yuan/ton.

2.3 Optimization Algorithms

Particle swarm optimization (PSO) algorithm is a typical swarm intelligence algorithm, which is derived from the research on bird predation. The PSO algorithm first initializes a group of particles in the feasible solution space. Each particle represents a potential optimal solution to the extreme value optimization problem, and the particle characteristics are represented by three indicators: location, speed, and fitness value. Then the particles move in the solution space, and the individual position is updated by tracking the individual extreme value pbest and the group extreme value gbest. The individual extreme value pbest refers to the position where the fitness value is the best calculated in the position experienced by the individual, and the group extreme value gbest refers to the position according to its own speed, individual optimal position and group optimal position, and updates the individual optimal position and group optimal position by comparing the fitness value. The update publicity is as follows (9):

$$V_i^{k+1} = w * V_i^k + c_1 r_1 * \left(X_{p \text{ best}}^k - X_i^k \right) + c_2 r_2 * \left(X_{g \text{ best}}^k - X_i^k \right)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1}$$
(9)

In the formula, X represents the particle position; V is the particle velocity; i is the i-th particle in the population; k is the number of iterations; w is the inertia factor, which represents the ability of particles to maintain their original velocity. In the basic particle swarm algorithm, this value is c_1 and c_2 , which respectively represent the ability of particles to learn from individual and group optima. This value can be manually adjusted; r_1 and r_2 are population diversity parameters, which are random numbers between 0 and 1. The algorithmic procedure is schematized in Fig. 1 below:



Figure. 1 Schematic diagram of the particle swarm algorithm process

A larger value of inertia weights is good for global search, and a smaller value of inertia weights is good for local search. During the whole optimization process, a strong global search capability is needed at the beginning of the iteration to allow the population to traverse the feasible solution space as soon as possible, and a strong local search capability is needed at the end of the iteration to accelerate the convergence of the algorithm with more accurate search. In order to balance the algorithm's full search and local search capabilities, the following simple inertia weight formulas are commonly used:

$$w(k) = ws - (ws - we)(Gm_{ax} - k)/G_{max}$$
⁽¹⁰⁾

$$w(k) = w_s - (w_s - w_e)(k/G_{max})^2$$
(11)

$$w(k) = w_s + (w_s - w_e)[2k/G_{max} - (k/G_{max})^2]$$
(12)

$$w(k) = w_e * (w_s/w_e)^{1/(1+10k/Gmax)}$$
(13)

In the formula, thew(k) for the iterationk Second time inertia weight; w_s is the initial inertia weight, w_e is the inertia weight for the maximum number of iterations, the $w_s = 0.9$, $w_e = 0.4$ when the algorithm performs optimally; the G_{max} is the maximum number of iterations.

In this paper, the particle swarm algorithm chooses the third nonlinearly decreasing inertia weight improvement formula, the inertia weight decreasing rate is fast and then slow, and switches from global search to local search faster, and stays in local search for a longer time.

3 Analysis of results

3.1 Analysis and validation of computational results

The time of t=1 is 10:00 am when the sun rises completely, ensuring the 24-hour cycle of charging and discharging of energy storage equipment. According to the aforementioned particle swarm optimization algorithm, MATLAB software is used for programming and calculation.

	wind turbines	photovoltaic modules	cogeneration of electricity and heat	hydrogen energy storage	system costs
Preferred model	500	60	1	1	85486
Alternate models	510	62	1	1	85579

Table 1. Calculation results table

As can be seen from Table 1-2, the preferred model has a lower total system cost. The wind resource situation of the project site is good, so more WTGs are selected. Typical winter days in this paper's calculations are in the time of the year when the wind resource situation is general, from the perspective of the whole year, the alternative WTG model wind resource utilization will further increase, the system cost will be reduced . Therefore, the higher cut-in wind speed and higher rated wind speed WTGs are advantageous, and therefore optimal from the perspective of the whole system. The preferred model is finally selected as the final optimal calculation result. In the end, the preferred model is chosen as the final optimal calculation result

Table 2. Statistical table of the results of the optimization calculations

Туре	Wind turbine (MW)	PV module (MW)	Electric heat cogeneration (MW)	Hydrogen energy storage (MW)
Number of units	500	60	5	1
unit capacity	1.5	5	100	550
total capacity	750	300	500	550

The net present value of the total investment in major equipment is 8,548.6 million yuan. Verification of capacity allocation results In this paper, the optimization problem of capacity allocation of integrated energy system in a certain area is studied, and the goal is to optimize the system under the constraints of ensuring system stability, so as to provide a reference for the design of power generation system in a certain area of the

latter. Therefore, it is necessary to analyze the reasonableness of the capacity allocation results.

3.2 Capacity Allocation Analysis

The ratio of the individual capacity of the system equipment to the total capacity of the system, as specified in the relevant regulations for power construction, should exceed 8%.

$$max(Pw_r, Pp_r, Pd_r) \ge W * 8\%$$
⁽¹⁵⁾

In the formula, the W is the total system power supply capacity.

The above capacity configuration results show that the total capacity of 500 wind turbine generators with a capacity of 1.5 MW is 750 MW, the PV modules with a capacity of 300 MW, and the electric heat cogeneration generator with a capacity of 500 MW. 550MW electric hydrogen production plant with total storage energy of 3500MWh. The total power supply capacity is 1550MW, that is, W=1550MW. 8% of 1550MW is about 124 MW.

The final configuration is shown in Table 3:

Table 3. Statistical table of final configuration results

Wind turbine (MW)	PV module (MW)	Electric heat cogeneration (MW)	Hydrogen energy storage (MW)
1.5 MW	60MW	500MW	3500MWh
500 units	5 squares	1 unit	1 unit
750MW	300MW	500MW	3500MWh

4 Conclusion

According to the characteristics of wind and light resources on the project site, this paper preliminarily selects the main power equipment of the integrated energy system. The wind turbine unit selects the low temperature and high altitude model suitable for the wind speed area, the photovoltaic module selects the monocrystalline silicon module with high cost performance ratio, and the energy storage equipment and electric power plant generator select the existing types in a certain place. The relevant calculation parameters of the capacity matching model are listed, such as the unit price of main selected equipment, system conversion efficiency, rated power, charging and discharging power limits, and system constraint index settings. The capacity allocation model is programmed by using particle swarm optimization algorithm and MATLAB software. Finally, the calculation results are analyzed and verified, which shows that the capacity allocation optimization method in this paper is effective.

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