Research on optimal dispatching model of clean energy generation grid-connected low-carbon power system based on system dynamics

Zhang Tiancheng

Faculty of Science, University of Malaya, Kuala Lumpur, Malaysia

Abstract

Considering the cost of carbon emission, an optimal dispatching model for low-carbon power system including thermal power, clean energy generation and energy storage facilities is established. Based on the theory of system dynamics, a dynamic model of carbon emission system is established. For hydro-thermal power systems, a hydro-electric peak-shaving model is established with the objective of minimizing the output adjustment of thermal power units and the system fuel consumption, and a hydro-electric peak-shaving model with the objective of maximizing the hydro-electric power generation and minimizing the system fuel consumption. The clean energy generator set is introduced into IEEE reliability testing system, and the grid connection scenarios of wind power, solar power generation, wind storage complementation and other clean energy power generation are selected to combine different carbon emission price levels. According to the simulation results, the different impacts of grid connection of clean energy power generation on low-carbon power system scheduling, emissions and operating costs are emphatically analyzed.

Keywords: System dynamics, clean energy for power generation, low carbon power system, optimal scheduling, carbon emissions

1. Introduction

As a basic key industry for national development, power industry plays a vital role in China's economic development [1]. At the same time, the negative impact of the development of the power industry on the ecological environment of various countries in the world has made various countries in the world pay more and more attention to the problem of gas emission from the power industry. With the increasingly serious greenhouse effect, the development of the power industry will be subject to certain restrictions and challenges [2]. Energy-saving power generation dispatching is an important reform to the existing power dispatching mode in China. The core is to break the existing power generation dispatching planning system, change the current dispatching mechanism of evenly distributing power generation, introduce energy conservation and emission reduction into the power system dispatching objectives, formulate the unit ranking table according to the unit energy consumption level, and give priority to non-fossil energy and low energy consumption units for power generation [3]. Vigorously developing clean energy sources such as wind power and adjusting the power supply structure have become a major measure to deal with this problem. Wind power output has the characteristics of intermittence, randomness and reverse peak regulation, which will affect the safe and stable operation of the power system when wind power is connected in large scale. Therefore, the objective function of low-carbon power system optimal scheduling for grid-connected clean energy generation is to minimize the system operation cost by adjusting the output

of all generator units in the system.

2. Overview of System Dynamics

System Dynamics (SD) is a comprehensive discipline based on computer simulation technology and feedback control theory. Through functional analysis, it analyzes and solves complex dynamic information feedback system problems and communicates natural science and social science [4]. System dynamics combines the knowledge principles of system theory, cybernetics and information theory, combines quantitative and qualitative methods, and uses computer simulation technology to analyze the internal dynamic structure and behavior of the system and find out the optimal solution. It is suitable for solving the problems in the nonlinear complex system composed of economy, society, environment and energy. In SD method, the observation, modeling and result analysis of social and economic system are completed by human beings, while the tracking of dynamic process of system is completed by computer [5]. In the early 1980s, Chinese scholars introduced it into China and began its new exploration in the field of scientific research in China. It was initially applied in the mid-1980s [6]. By the 1990s, system dynamics had been fully developed in the fields of natural science, social science and engineering technology in China. The system dynamics model can reflect the interaction between the structural functions and dynamic behaviors of complex systems, and is suitable for dealing with complex socio-economic and ecological environment problems with low precision requirements [7]. At present, system dynamics has been widely used in the field of ecological environment research in the world. System dynamics is a method that combines the advantages of people's keen observation on things, creativity and imagination with the ability of computers to perform complex operations and effectively exerts their respective advantages.

2.1. Structural analysis and establishment of optimal dispatching model for grid-connected low-carbon power system with clean energy generation

System modeling. The first step in the application of system dynamics modeling is to determine the research objects and problems. Before modeling, you should have a specific understanding of the research objects, determine the problems, and then carry out targeted modeling. The enhancement of energy utilization efficiency is the result of the combined effect of energy structure optimization and technological progress. Based on this, this paper establishes a low-carbon emission reduction model from the two influencing factors of industrial energy consumption and carbon emissions per unit of energy. The carbon emission system is divided into carbon emission energy subsystem, primary industry carbon emission subsystem (including three ecosystems of agriculture, forestry and animal husbandry), carbon emission economic subsystem, carbon emission population subsystem and carbon emission environment subsystem. The initial carbon emission amount is generally determined on the principle of free distribution, based on the collection and comparison of different emission levels of the same unit in the same industry, and after considering the national emission reduction target, industry quota gap and other factors, the excess or deficiency can be traded in the carbon emission market. The establishment of the scheme is related to the optimization objectives of the unit, so multi-scheme management means multi-objective planning [8]. Different schemes can be realized by establishing schemes considering different optimization objectives, different input data and different calculation parameters. When the carbon emission quotas of conventional thermal power units and carbon capture units are less than their own carbon emissions, they need to purchase carbon emission quotas to pay a certain economic cost. In addition to these two causal relationships, there are related causal relationships between other subsystems and within subsystems. Through the interaction of causal relationships, model simulation is realized.

The fuel consumption cost function of a thermal power generation unit can be expressed as the product of the price of a given type J fuel and the total amount of fuel burned per hour, as shown in equation (1) [9]:

$$k_j = \frac{R_j}{Dj} \times Uj \times \text{Re}_j$$

$$(1)$$

The CO_2 emissions of thermal power generating units can be obtained by calculating the average carbon content of fuel combustion, and the CO_2 emissions of thermal power generating units can be expressed as:

$$R_j = \frac{f_{ij}}{Tj} \times S_j$$

(2)

The CO_2 cost function of thermal power generating units can be expressed as the product of carbon emission price and total CO_2 emission, as shown in equation (3):

$$S_j = \frac{1}{\sum_{i=1}^{n}(S_r)}, (0 < (S_j) \leq 1)$$

(3)

The fuel-emission cost function of the thermal power generation unit is the sum of the fuel consumption cost function and the carbon dioxide emission cost function, as shown in equation (4):

$$D_j = \sum_{i=1}^{n}(H_P \times V_p)$$

(4)

The key elements in each subsystem of the carbon emission system interact with each other and are contained within the boundaries of the system, forming a complex network of relationships. Then the feedback loop is used to reflect the interaction results between different information and actions. There is a positive correlation between them. Secondly, there is also a positive coupling between the energy system and the environmental system. There is no doubt that most of the causes of global warming and regional environmental deterioration are caused by the wanton emission of pollutants after fossil energy consumption. The source of carbon emission in the power system is the combustion of fossil fuel when the thermal power unit is generating electricity. When the unit is working in DPR state, its working conditions and parameters deviate from the design values, and the energy conversion efficiency of the unit is greatly reduced. If the unit has the decomposed power of the annual contract power in that month, the startup plan shall also be ensured to ensure that the unit can complete the contract power [10]. Due to the inaccuracy of monthly load forecasting and the uncertainty of future power grid operation mode, the monthly unit combination scheme cannot finely consider the safety constraints of power grid operation. In order to deal with the uncertainty of the load, the system needs to provide certain rotating backup to ensure the safe and stable operation of the power system, mainly to deal with the fluctuation of unit output caused by the uncertainty of the load. Not all practical factors have been taken into account. Because we only need to understand the basic behavior trend of carbon emissions, we do not need to obtain accurate data, so we do not need very high precision.

2.2. Model variables and parameters

Empirical formula method. Some empirical formulas in the existing research are used for reference to determine the relationship between various elements. Years of arithmetic mean. Some parameters can express the average level of parameters by arithmetic or geometric mean of their multi-year historical data. System dynamics mainly studies the dynamic feedback relationship between various variables in the system, and is not sensitive to the changes of internal parameters of the model, so long as the estimated parameters can meet the requirements of the model. Some of the parameters in this paper are determined by collecting data, analyzing information and relevant research, and then making predictions. Deep depression force makes the rotor bear large alternating thermal stress. After a certain cycle, fatigue cracks will occur on the metal surface and gradually expand to fracture. Energy consumption initial value, C2: primary industry GDP initial value, C3: total population initial value, C4: energy demand elasticity, C5: structural adjustment factor, C6: carbon emission initial value, C7: total livestock number initial value, C8: forest coverage initial value. In order to further control the total amount of carbon emissions, this paper constructs a ladder-type carbon transaction cost model. Based on the carbon emission quota, several emission intervals are set, and the higher the emission interval, the higher the corresponding price coefficient. The environmental protection dispatching mode aims at minimizing the emissions of sulfur dioxide and carbon dioxide, and

prepares a day-ahead power generation plan curve under the condition of meeting various constraints. According to the emission intensity of carbon dioxide and sulfur dioxide from thermal power units, thermal power units with low average emission will be given priority.

Equal load rate is to solve the problem by taking equal load rate of units as the goal in the modeling of day-ahead dispatching plan. The result is to pursue the principle of equal average load rate as much as possible under the condition of conforming to unit constraints and network constraints. R1: Birth Rate, R2: Mortality Rate, R3: GDP Growth Rate, R4: Cultivated Land Increase Rate, R5: Cultivated Land Decrease Rate, R6: Energy Consumption Growth Rate, R7: Livestock Quantity Change Rate, R8: Forest Disaster Loss Rate. Initial value refers to setting variables that need to be given initial values in the model. There are 5 variables that need to be given initial values in Tianjin's carbon footprint system. Firstly, the starting and stopping states of conventional thermal power units, demand-side low-carbon resources and carbon capture units are randomly initialized, and then the output and carbon capture power of the carbon capture units are randomly initially generated according to the starting and stopping states of conventional thermal power units, demand-side low-carbon resources and carbon capture units, instead of the carbon capture power of the carbon capture units being set to 0. When the predicted output of wind power is greater than the actual output, the power shortage is met by increasing the output of thermal power units. If there is insufficient space for thermal power to increase, the load will be cut off. Classify and query monthly power generation plans compiled by the system or manually adjusted, and support query of unit plans and tie-line plans according to different levels of units, power plants, regions, etc.

2.3. Model validation

Visual inspection means that through in-depth analysis of the existing data, the system model's variable setting, causality, flow chart structure and equation expression are verified to be correct. In the process of establishing the equation, the model in this paper has passed the above tests. Based on the purpose of modeling the whole system, this paper starts with three subsystems of population, economy and energy, selects three key indicators of Tianjin's resident population, gross industrial output value and energy consumption demand, calculates the relative error between the actual value and the simulated value in the first five years to test the accuracy of the model. Similar to CO_2 emissions, the change in system operating costs is not linearly related to installed capacity. Due to the high capacity of solar power generation, most of the coal-fired generators stop running after the solar energy is connected to the grid, thus the running cost of the system after the solar energy is connected to the grid is the lowest. Whether the demand-side low-carbon resources and the start-up and stop-down time constraints of the carbon capture unit are met, if not, the start-up and stop-up states of each part are trimmed, if the constraints are met, the output of each part is adjusted according to the adjusted start-up and stop-up states, and whether the output constraints are met is judged. The network loss in the energy-saving scheduling mode is also the smallest in all scheduling modes. Therefore, it can be considered that the energy-saving dispatching mode in the system has good effects on saving energy and reducing network loss, basically achieving the expected goals of reducing coal consumption and optimizing network loss, and meeting the requirements of energy-saving power generation dispatching.

Table 1. Energy consumption demand

Energy Consumption Demand/10,000 Tons	2015	2016	2017	2018
Actual	4997.36	6745.42	8499.68	18949.46
Simulation	4882.33	6816.27	8744.29	19568.61
Difference rate	0.0021%	-2.8763%	-2.6628%	4.8316%

As there are many influencing factors in the socio-economic system and the relationship between them is more complex, the system is not sensitive to parameter changes and has certain stability. The primary industry carbon emission system should also have such stability. Generally speaking, the allowable error range of the system dynamics model is within 15%. From the results shown in Table 1 above, except that the

deviation rate of gross industrial output value in 2018 is 10%, the rest is within 5%, and the operation results meet the requirements, i.e. the simulation results of the model are well fitted with historical data, and subsequent tests can be carried out. Compared with the wind power output curve with medium volatility and high volatility, the system with low volatility wind speed output curve has lower operating cost, because the wind power output curve with low volatility can generate more available energy. However, the wind power output curve with higher volatility generates less energy, so its operation cost is relatively high. The change of population will cause a series of changes including environment, resources, economic situation and social changes. Controlling the speed of population development commensurate with the level of production development is an important aspect of system development. In this system, both the energy-saving dispatching mode and the environmental protection dispatching mode have good environmental protection effect, can effectively reduce the emission of carbon dioxide and sulfur dioxide, reduce the emission level of greenhouse gases and polluting gases, and have positive effects on emission reduction.

3. Case Study

3.1. Example data

Introduced clean energy generating units in the IEEE reliability test system to study its impact on CO2 emissions. The access point of the three low-carbon clean energy generating units is node 8, the generating capacity is 100MW, and it is integrated into the IEERTS system through a newly-built line. The length of the carbon emission interval is d = 100 t; the increase in the price of carbon trading at each step is τ = 25%. The standard deviation of wind power output prediction error is 25% of the predicted output. Assuming that the system's regional power marginal emission factor OM is 0.8593, and the capacity marginal emission factor is 0.3367, the grid baseline emission factor of the system is 0.648 based on the weighted average of 55% of each weight. It takes 24 hours to obtain daily load and power generation data, and 8,760 hours to obtain annual data. Table 2 summarizes various simulation cases and their specific descriptions, including power generation and load data, solution algorithm and CO_2 price.

Table 2. Simulation example and description

Case	Low carbon clean energy		Load curve	Carbon price ($/t^{-1}).	Solving algorithm	Time /h
	Type	Curve				
1	The wind	Less fluctuation	Typical summer	0	OPK	24
2	The wind	Medium fluctuation	Typical summer	0	OPK	24
3	Solar energy	Less fluctuation	Typical summer	50	OPK	24
4	Solar energy	High fluctuation	Typical summer	0	OPK	24

3.2. Results and analysis

Tables 3 and 4 show the results of changes in the total emissions of CO2 and changes in the operating costs of the system respectively.

Tables 3. CO_2 Changes in Total Emissions

Case	Grid-connected capacity of low-carbon clean energy power generation/MW					
	100	200	300	Reach the first 100	Reach the second 100	Reach the third 100
	CO2 total emissions			CO2 emission changes		
1	28503	27941	29916	1428	1252	1213
2	31256	25446	29098	614	870	554
3	28691	30124	25138	377	361	355
4	33842	30241	29901	371	582	571

Table 4.The operating cost of the system and its changes

Case	Grid-connected capacity of low-carbon clean energy power generation/MW					
	100	200	300	Reach the first 100	Reach the second 100	Reach the third 100
	Total operating cost of the system			Change in total operating cost of the system		
1	1427836	1876727	1767456	12327	68745	12772
2	1378911	1278677	2757411	37457	15784	28587
3	2289814	2983453	2767448	29645	67414	47574
4	3754578	3747487	1974744	67457	57434	39874

When the carbon emission price is 50 \$/t, the operating cost in the system is higher than when the carbon emission price is 0 \$/t, because coal and gas power generation need to pay the carbon emission price, and wind energy and solar energy need to pay a higher node marginal price due to the carbon price. The operating cost of the system when the carbon emission price is 50 \$/t is shown in Fig. 1.
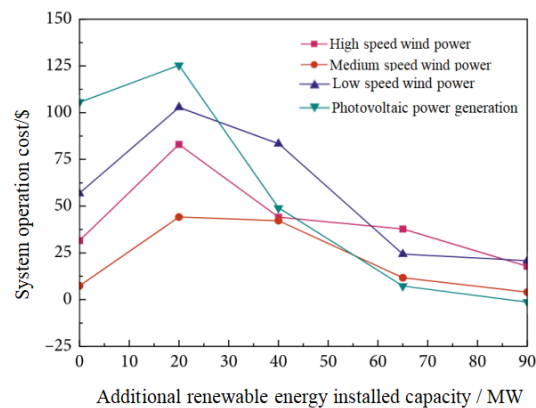

Fig. 1. The daily operating cost of the system when the carbon emission price is \$/t

After the low-carbon clean energy generating units (fans and solar generators) are merged into FFEERTS, the scheduling of coal-fired units and gas-fired units in the system is reduced. Thermal power units do not participate in deep peak shaving, and carbon transaction costs are not considered in the objective function. During the flood season, the inflow of water is especially abundant. If hydropower peak shaving mode is adopted, a lot of waste water will be generated, which is not conducive to the full utilization of hydraulic resources. In these simulation results, when all the gas units reduce or reduce their output to 0, the coal-fired units reduce their output at non-peak load. With the increase of load demand, the output of coal-fired units will also continue to increase. At the same time, for the sake of safety, the regulation capacity of hydropower units will be greatly weakened. Judging from the regulation amount of thermal power units, there is not much difference between the peak regulation strategies of hydropower and thermal power. Thermal power units do not participate in deep peak shaving, and carbon transaction costs are considered in the objective function. Compared with the wind power output curve with medium volatility and high volatility, the system with wind speed output curve with low volatility has lower operating cost, because the wind power output curve with low volatility can generate more available energy. However, the wind power output curve with higher volatility generates less energy, so its operation cost is relatively high.

4. Summary

In this paper, a low-carbon power system optimal scheduling model for grid-connection of clean energy power generation is constructed. The effects of grid-connection of various clean energy power generation on system scheduling, carbon emissions and operating costs are investigated. Based on the theory of system dynamics, a dynamic model of carbon emission system in the primary industry is constructed. A step-by-step carbon transaction cost model is introduced into economic scheduling to realize the low-carbon economic operation of the system. Energy-saving dispatching mode plays a positive role in realizing energy saving and

emission reduction of power system. According to the definition of energy-saving power generation dispatching, combined with the actual situation of power grid energy-saving dispatching simulation mode, the connotation of energy-saving dispatching is deeply analyzed from the aspects of saving fossil energy, reducing network loss and playing the substitute role of renewable energy. In contrast, the system design of carbon market transaction is more complex, restricted by multiple factors in the whole system, all factors need to be linked to achieve the goal of carbon emission reduction, and the emission reduction time point appears later than the carbon tax, i.e. the lag of carbon emission reduction. Although carbon emission price has no influence on the operation of wind power and solar power generation, the implementation of carbon emission price increases the power generation cost of fossil fuel units, thus stimulating the investment of wind power and solar power.

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

All by TIANCHENG ZHANG

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