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Long-term Investment Planning Model for Power Generation Capacity Based on Harmony Search Algorithm with Particle Swarm Optimization

Chai Dapeng, Ma Mingjuan, Xue Song, Shi Hui and Zeng Ming
School of Economics and Management, North China Electric Power University, Beijing, 102206, China

Abstract: Under the condition of large-scale renewable energy integrated into grid, optimizing generation capacity investment needs to achieve large-scale renewable energy integrated into grid and to take into account the economic and environmental benefits. In view of the long-standing problem of uncoordinated power generation capacity investment, firstly, this study built a planning model of long-term investment in generation capacity based on minimized investment costs and minimized CO_2 emissions. Secondly, the mechanism and procedure of harmony search algorithm with particle swarm optimization was introduced. Finally, the impact of different hydropower capacity and wind power capacity on portfolio investment cost of generation capacity and CO_2 emissions were analyzed combined with scenario simulations. In addition, long-term investment planning program of generation capacity was optimized in both economic and environmental benefits aspects. From the study results, it can be seen that the total cost is 2027421.34 and 158141.04 Yuan in R0 and R9 of the wet season scenario and the total CO_2 emissions is 208.43 and 70.62 in R0 and R9 of the wet season scenario; the total cost is 158723.56 and 206782.12 Yuan in S0 and S9 of the dry season scenario and the total CO_2 emissions is 218.91 and 74.74 in S0 and S9 of the dry season scenario. Based on this, complementary operation and optimization investment of hydro-thermal power-wind power was achieved. This study will provide a theoretical reference for policy makers.

Key words: Portfolio investment of generation capacity, investment cost, CO_2 emissions, harmony search algorithm, particle swarm optimization

INTRODUCTION

Rapid growth of electricity demand and coal-based power structure are the main features of the power industry in China (Yu *et al*., 2010). During the "Twelfth Five-Year" period, China proposed energy strategic plan of scientific, green, low-carbon. And this energy strategic plan requires speeding up energy structure adjustment, vigorously developing new energy industry and implementing the target of non-fossil energy consumption increased to 15% till the year 2020 (Xiong and Qi, 2011). Therefore, it is of practical significance adjusting power structure, reducing coal power proportion and vigorously developing renewable energy which not only meet China's energy strategic plan, but also meets the requirements of building a modern energy industry system (Teng *et al*., 2008).

The existing literatures of renewable energy generation capacity optimization have mainly focused on complementary operation of renewable energy power generation technology (Li *et al*., 2007) and optimal scheduling (Vieira and Ramos, 2009). Zhang *et al*. (2012) build a simulation model of the wind-water-thermal power complementary system and studied the effects of wind power capacity ratio on the stability of wind-water-thermal power complementary system. In view of this situation, firstly, this study builds a planning model of long-term investment in generation capacity based on minimized investment costs and minimized CO_2 emissions. Secondly, the mechanism and procedure of harmony search algorithm with particle swarm optimization will be introduced. Finally, long-term investment planning program of generation capacity is analyzed under different situations combined with scenario simulations.

MATERIALS AND METHODS

Objective functions: The first objective function is minimized portfolio investment costs of generation capacity, as shown in Eq. 1:

$$\begin{aligned}\min C = \sum_{t\in T}\sum_{n\in N}[(CI_n \frac{j(1+j)^t}{(1+j)^t-1} + CF_n)P_n(1+j)^{-t}] + \\ \sum_{t\in T}\sum_{m\in M}\sum_{i\in I}[(CV_i + CF_i + CP_i + CE\times\lambda_C)P_{i,m,t}\Delta_m(1+j)^{-t}]\end{aligned} \tag{1}$$

Corresponding Author: Chai Dapeng, School of Economics and Management, North China Electric Power University, Beijing, 102206, China

where, C denotes portfolio investment costs of generation capacity; T denotes time; N denotes new units of generation capacity; M denotes the months considered in each plan year; I denotes all units; CI_n denotes the investment costs of new units (y MW^{-1}); j denotes annual discount rate; tn denotes lifetime of new units (years); CF_n denotes fixed operation and management costs of new units (y MW^{-1}); P_n denotes installed capacity of new units (MW); CVn denotes variable operation and management costs of new units (y MW^{-1}); CPi denotes pumping cost of unit I (y MW^{-1}); CF_i denotes fuel cost (y MW^{-1}); CE denotes subsidy cost of CO_2 emission (y ton^{-1}); λ_c denotes CO_2 emission factor (tony $MW^{-1}h^{-1}$); $P_{i,m,t}$ denotes generation in month m, year t of unit i. Δm denotes generation hours of units (h).

The second objective function established is shown in Eq. 2:

$$\min EC = \sum_{t\in T}\sum_{m\in M}\sum_{n\in N} CO_{2i} P_{i,m,t}\Delta m \tag{2}$$

Constraints

Electricity demand constraints: The total generation capacity of all units should meet load demand of the planning period (Zhang *et al*., 2010), including power consumed by units for generating power, as shown in Eq. 3:

$$D_{m,t} - P_{m,t} \le [\sum_{s\in S} P_{s,m,t} - \sum_{p\in Pump} P_{p,m,t}]\Delta m,\ \forall t\in T \tag{3}$$

where, $D_{m,t}$ denotes power demand in moth m, year t; $P_{m,t}$ denotes generation capacity of renewable energy generation units (except for large-scale hydropower and wind power) and cogeneration units (MWh); S denotes installed capacity of all units s(excluding pumped storage units); Pump denotes installed capacity of pumped storage units.

Installed capacity constraints: Assuming the utilization rate of thermal power units fixed, while coal-fired units and fuel unit utilization rate are of 92% and CCGT unit utilization rate is of 94%. Installed capacity constraints of units are as shown below in Eq. 4 to 5:

$$P_{e,m,t} \le \alpha_{e,m} \times P_{e,t}\quad \forall e\in T\_E \tag{4}$$

$$P_{n,m,t} \le \alpha_{n,m} \times P_{n,t}\quad \forall n\in T\_N \tag{5}$$

where, $\varphi_{e,\,m}$ denotes the utilization rate of thermal power unit e in moth m; $P_{e,t}$ denotes installed capacity of thermal power unit e in year t.; T_E denotes existing thermal power units; T_N denotes new thermal power units.

Wind power constraints: The following constraints should ensure that wind power capacity is equal to its installed capacity, as shown in Eq. 6 to 9:

$$P_{n,m,t} = \alpha_{n,m} \times P_{n,t}\quad \forall n\in N\_W \tag{6}$$

$$P_{e,m,t} = \alpha_{e,m} \times P_{e,t}\quad \forall e\in E\_W \tag{7}$$

$$P_{n,t} \le ONV\quad \forall n\in N\_Onshore \tag{8}$$

$$P_{n,t} \le OFV\quad \forall n\in N\_Offshore \tag{9}$$

where, N_Onshore is for onshore wind power turbines; ONV is for the largest installed capacity of onshore wind power turbines; N_Offshore is for offshore wind power turbines; OFV is for the largest installed capacity of offshore wind turbines.

Large-capacity hydropower constraints: Reservoir constraints and pumping capacity constraints for large hydropower units are as shown in Eq. 10:

$$\begin{aligned} reser_{1,t} &= reser_{12,t} + Inf_{1,t} \\ &-(\sum_{n\in N\_H} P_{n,1,t} + \sum_{n\in E\_H} P_{e,1,t})\times\Delta_1 + \sum_{p\in Pump} P_{p,1,t}\times\Delta_1 \end{aligned} \tag{10}$$

where, $reser_{m,\,t}$ is for the reservoir water storage in month m, year t ; $Inf_{m,\,t}$ is for reservoir water injection in month m, year t ; N_H and E_H, respectively represents new large hydropower units and existing large hydropower units.

Maximum storage capacity and minimum storage capacity of the reservoir are as shown in Eq. 11 and 12:

$$reser_{m,t} \le \max R\quad \forall t\in T\ \forall m\in M \tag{11}$$

$$reser_{m,t} \ge \min R\quad \forall t\in T\ \forall m\in M \tag{12}$$

where, maxR and minR, respectively represents maximum and minimum storage capacity of the reservoir.

IMPROVED HS-PSO OPTIMIZATION ALGORITHM

Traditional HS algorithm: Harmony Search Algorithm (Harmony search, HS), a modern heuristic intelligent evolutionary algorithm, created by Geem through the similarity of music and optimization problems. Harmony search algorithm is described as follows:

Initialization of the optimization problem: The optimization problem is described as follows:

$$\text{Object equation: } \min F(x)$$

where, x is for each set of design variables (x_i); X_i is for the range ($Lx_i < X_i < Ux_i$); N is for the number of design variables.

Initialization of sound memory : The sound memory (HM) matrix is shown in Eq. 13:

$$HM = \left[\begin{array}{ccccc} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{array}\right] \begin{array}{l} \Rightarrow f(x^{(1)}) \\ \Rightarrow f(x^{(2)}) \\ . \quad . \\ . \quad . \\ . \quad . \\ \Rightarrow f(x^{(HMS-1)}) \\ \Rightarrow f(x^{(HMS)}) \end{array} \tag{13}$$

A new harmony improved from the HM set: Memory consideration: when HS detemines x_i', x_i^j can be chosen at random within HM (HMCR, j = {1,2…HMS}):

$$x_i' \leftarrow \begin{cases} x_i' \in \{x_i^1, x_i^2 \cdots x_i^{HMS}\}, \text{ withHMCR} \\ x_i' \in X_i, \text{with(1-HMCR)} \end{cases} \tag{14}$$

Update the HM: If new Harmony vector $(x' = (x_1', x_2', \cdots x_n'))$ is better than the worst harmony in the HM, new harmony will enter HM $(x' = (x_1', x_2', \cdots x_n'))$ and the existing worst harmony will be omitted from the HM.

Approve suspended standard: If New Harmony vector meets suspended standard based on the maximum number, the calculation is terminated, otherwise, repeat steps 3 and 4.

HS-PSO optimization algorithm: The process of HS-PSO Optimization Algorithm is as follows:

- Initialization parameter setting. Set the maximum particle swarm iterations, initialization times and chaotic particle swarm population size and parameters of the position, as well as initializing parameter of harmony search algorithm and harmony memory (Sun *et al*., 2012)
- Update a body and the global optimum position fitness value so as to calculate the speed of calculation
- Apply the chaos theory to find the most optimal solution if the new location of these particles meet the requirements of the output current
- Update the position and velocity of particle swarm after chaotic
- Apply HS to conduct global search and update harmony memory. If the fitness is better than the candidate solutions in harmony memory, then the new solutions will replace harmonies library harmony vector candidate solutions
- Evaluate the populations of all particles and update its global optimal solution
- Verify if the test scale to the maximum number of iteration times, if not, turn to step 2. Otherwise, exit the loop and output iterations search results

RESULTS

Along with the rapid development of social and economic, China's electricity demand continues to increase. According to the forecast conducted by relevant power sector, China's electricity demand growth rate will reach 4.4% in 2020. According to statistics published by China Electricity Council, thermal power and hydropower are still dominant and new installed capacity, respectively is 12.25 million kW and 58.86 million kW till the end of 2011. In addition, the installed capacity of renewable energy is increasing. New solar power and wind power connected with grid reached 19.28 million kW till the end of 2011, among which the installed capacity of wind power respectively account for 21% of the total installed capacity and 50% of renewable energy capacity.

Since long-term coordination investment planning model for generation capacity in this study is nonlinear programming, two single-objective optimization problems will be solved firstly for sensitivity analysis of multi-objective equations. Under the scenario of wet season period, the optimal scheme of two single-objective equations, respectively are R0 and R9, while under the scenario of dry season period, the optimal scheme are S0 and S9, as is shown in Table 1.

Table 1: Simulation results under different scenario during planning period

	Wet season scenario during the planning period		Dry season scenario during the planning period	
Parameters	R0	R9	S0	S9
Total cost (Y)	158141.04	2027421.340	158723.56	206782.120
Unit cost (y MW^{-1} h^{-1})	240.63	326.860	241.38	331.730
CO_2 emissions/uint (million tons $unit^{-1}$)	0.316	0.107	0.33	0.113
Total CO_2 emissions (million tons)	208.43	70.620	218.91	74.740

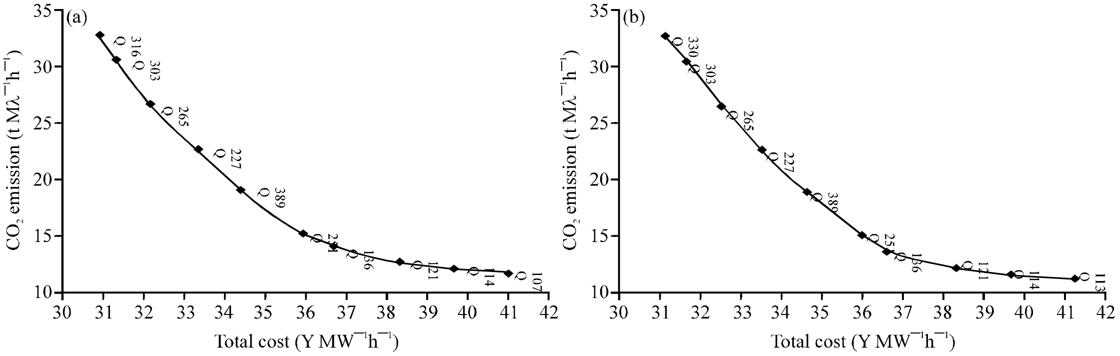

Fig. 1(a-b): (a) Pareto curve of long-term investment for generation capacity under wet season scenario and (b) Pareto curve of long-term investment for generation capacity under dry season scenario

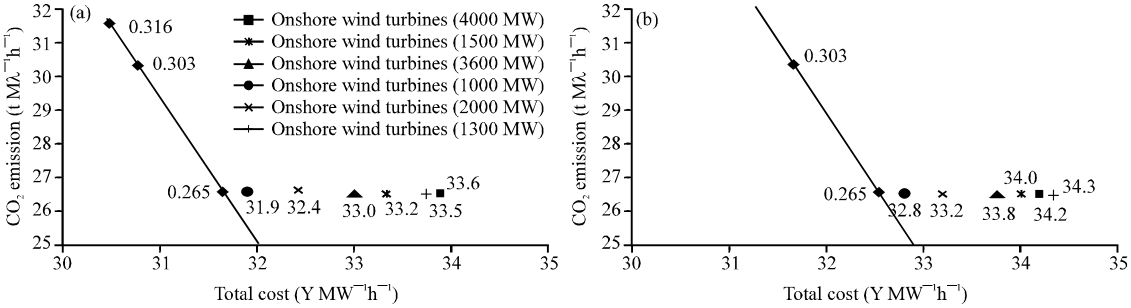

Fig. 2(a-b): (a) Investment costs and CO_2 for generation capacity under wet season scenario and (b) Investment costs and CO_2 for generation capacity under dry season scenario

It can be seen that the portfolio investment costs of generation capacity and CO_2 emissions in wet season scenario are significantly lower than the dry season scenario. It means that increasing the installed capacity of hydropower can reduce investment costs and CO_2 emissions so as to improve the economic and environmental benefits of electricity system. The Pareto curves of long-term investment for generation capacity under the two scenarios are shown in Fig. 1. Compare Fig. 1, the following conclusions can be drawn:

- With the continuous increase of the installed capacity for hydropower generation capacity, the economic and environmental benefits of the system have been improved. The optimal solution under wet period scenario not only reduces the portfolio investment cost of generation capacity, but also reduces CO_2 emissions which mean lower costs can reach the same CO_2 emissions
- In the case of certain power structure, reducing the CO2 emissions will increase the investment cost of the system, but this effect is non-linear. It can be seen from the Pareto curve that the slope of the curve gradually decreases along with the downward trend of the curve, which means lower cost can get the same CO_2 emission reduction benefits

This section below will study the effects of wind power installed capacity under scenario simulation on investment costs and CO_2 emissions of portfolio investment for generation capacity. Figure 2 show wind power installed capacity under the two scenarios on investment costs and CO_2 emissions. Compare Fig. 2, the following conclusions can be drawn:

- Compared with scenario R1, when new installed capacity of onshore wind power is 1800, 1300 and 1100MW investment costs gradually increase due to increasing offshore wind power installed capacity to meet CO_2 emission constraints will synchronously increase investment costs
- For certain investment costs, increasing the installed capacity of wind power will reduce installed capacity of thermal power and increase hydropower and wind power installed capacity. At the same time, the goal

of energy saving and emission reduction can be achieved by adjusting the structure of power generation capacity

CONCLUSION

Long-term coordination investment planning model for generation capacity, economic and environmental benefits considered, is conducted in this study. Besides, the optimal program of investment costs and CO_2 emissions are analyzed using harmony search algorithm. From the study, complementary operation and optimization investment of hydro-thermal power-wind power is achieved, which lays the foundation for long-term investment planning.

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