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Multi-objective Generation Expansion Planning for Integrating Large-scale Wind Generation

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SUMMARY

Due to the growth of energy consumption, the extensive use of conventional fossil fuels from the exhaustible resources and the environmental concerns, high penetration of renewable energy resources is considerably observed worldwide. Wind power generation is holding the first rank in terms of utilization and importance. In the last decade, the growth rate of the global installed wind capacity has been about 30% per annum. Denmark, Germany, and Spain are the first few countries generating 20% of their electricity from wind turbines.

However, wind resource is intermittent, stochastic and fluctuant, the large-scale integration of wind generation (WG) will bring new obstacles to generation expansion planning (GEP). In this paper, a multi-objective generation expansion planning (MOGEP) approach considering high wind power penetration was proposed in this paper, which optimizes three objectives simultaneously, namely the investment decision, CO_2 emission amount, and power outage cost. 1) The investment decision objective function is defined as the sum of

the discounted (present value) of the investment cost, O&M cost, minus benefits associated with the utilization of wind energy. 2) The amount of CO_2 emission can be determined by the emission rates of the different types of generation units. 3) Power outage cost can be evaluated by EENS index.

Considering the complex solution space, non-convex and nonlinear mixed integer objective functions, various approaches have been proposed to deal with GEP problem. Recently, people typically conclude that the heuristic methods can provide "high-quality" solutions in an acceptable computational time, even for large-scale problems. Several meta-heuristic methods have already been introduced in literatures, e.g. Genetic Algorithm, Simulated Annealing, Ant Colonies, Particle Swarm Optimal Algorithm (PSO), et al. In this paper, a two-phase multi-objective PSO (MOPSO) algorithm was introduced to solve this optimization problem, which can accelerate the convergence and guarantee the diversity of Pareto-optimal front set as well.

Case study based on a numerical test system is conducted to demonstrate the feasibility and effectiveness of both the proposed MOGEP approach.

KEYWORDS

Wind generation, multi-objective generation expansion planning (MOGEP), two-phase multi-objective PSO (MOPSO)

INTRODUCTION

In recent years, the renewable energy (Wind, PV, etc.) is critically improving the security of energy supply by drawing upon sustainable natural sources and reducing environmental impacts. The wind power generation is holding the first rank in terms of use and importance [1]. In the last decade, the growth rate of the global installed wind capacity has been about 30% per annum [2]. However, wind resource is intermittent, stochastic and fluctuant, the large-scale integration of wind generation will bring new obstacles to the GENSCOs' planning. The traditional single-objective approach is no longer suitable for the expansion planning of utilities [3-4].

In this paper, a multi-objective generation expansion planning (MOGEP) approach for

integrating large-scale wind power was proposed, which optimizes three objectives simultaneously, namely the investment decision, CO2 emission amount, and power outage cost. Accordingly, a two-phase multi-objective PSO (MOPSO) algorithm was introduced to solve this optimization problem, which can accelerate the convergence and guarantee the diversity of Pareto-optimal front set as well. Case study based on a numerical test system is conducted to demonstrate the feasibility and effectiveness of the proposed MOGEP approach.

PROBLEM FORMULATION

The GEP under the aid of the multi-objective models allows decision makers to grasp the conflicting nature and the trade-offs among different objectives in order to select satisfactory compromise solutions for the MOGEP problem. The proposed planning model minimizes different objective functions related to the total cost of investment, the amount of CO2 emission, and the outage cost. The detailed explanation of each objective function is as follows.

A.   Total investment cost

The total investment optimization problem is formulated in (1). This objective function is defined as the sum of the discounted (present value) of the investment cost for: C_1- added candidate generation units; C_2- O&M and variable operational costs for newly added and existing generation units; C_3- benefits associated with the utilization of wind energy. Each sort of cost can be indicated by (1-1)~(1-3), as follows:

$$O_{inv} = C_1 + C_2 - C_3 \qquad (1)$$

$$C_1 = \sum_{t=1}^{T}(1+r)^{-t}\sum_{i=1}^{N_g}(I_{it} - P_{it})G_{it}S_{it} \qquad (1\text{-}1)$$

$$C_2 = \sum_{t=1}^{T}(1+r)^{-t}\sum_{j=1}^{N}(F_{jt}G_{jt}n_{jt} + V_{jt}E_{jt}) \qquad (1\text{-}2)$$

$$C_3 = \sum_{t=1}^{T}(1+r)^{-t}(A_t + W_t)\sum_{k=1}^{N_w}E_{kt} \qquad (1\text{-}3)$$

where r is the interest rate, T denotes the length of planning horizon, t is the time period. During the time period t: N_n is the newly added candidate generation units, I_{it} and P_{it} represent the investment cost and salvage cost for new generation i ($/MW), separately. G_{it} / G_{jt} is the power capacity of generating unit i/j (MW), s_{it} is equal to 1 if generation unit i is built and 0 otherwise. N is the total generation units, including the existing and newly involved. F_{jt} is the fixed O&M cost of jth unit ($/MW), n_{jt} is the cumulative number of jth unit up to period t, V_{jt} is the variable O&M cost of generation unit j ($/MWh), E_{jt} / E_{kt} is the cumulative energy output of generation unit j/wind generation unit k (MWh). A_t is the average fuel cost in time period t (MW), W_t is the wind energy production index. N_w is conducted to the number of wind generation units.

B. CO_2 emission

The second objective function attempts to minimize the amount of CO_2 emissions. It can be determined based on the emission rates of the different technologies of generating units,

$$O_{emi} = \sum_{t=1}^{T}\sum_{j=1}^{N} B_{jt} E_{jt} \tag{2}$$

where B_{jt} is the amount of CO_2 emission generated by jth unit in time period t (t/MWh).

C.   Outage cost

The outage cost could depend on many factors, when a failure of energy supply occurs, including the types of customers interrupted, actual load demand at the time of outage, duration of outage and the time in which the outage occurs. In this paper, the outage cost is evaluated by EENS index, which can be expressed as

$$O_{out} = \sum_{t=1}^{T} (1+r)^{-t} H_t EENS_t \tag{3}$$

where H_t is the cost of energy not supplied (($/MWh), and $EENS_t$ [5]is the expected energy not served in (MWh).

D.   Problem formulation

The mathematical formulation of the proposed MOGEP approach is presented in (4), which optimizes three objectives, i.e. minimizing the investment cost, CO2 emission rate, and power outage cost, simultaneously. The constraints of construction upper limit, generation & demand, cumulative annual generation limits, and LOLP are illustrated in (4-1)~(4-4), and the

additional constraints are listed from (4-5)~(4-8).

$$\min \quad O(\mathbf{X}) = \{O_{inv}(\mathbf{X}), \ O_{emi}(\mathbf{X}), \ O_{out}(\mathbf{X})\} \tag{4}$$

$$s.t. \quad 0 \le \sum_{q=1}^{N_q} G_{qt} \le \overline{G_{qt}} \qquad \forall t \in T, \ q \in Q, \ q \in N_n \tag{4-1}$$

$$\sum_{j=1}^{N} G_{jt} U_{jt} n_{jt} \ge D_t \qquad \forall t \in T \tag{4-2}$$

$$8760 \times \underline{Gf_{jt}} G_{jt} U_{jt} n_{jt} \le E_{jt} \le 8760 \times \overline{Gf_{jt}} G_{jt} U_{jt} n_{jt} \qquad \forall t \in T, \ j \in N \tag{4-3}$$

$$\underline{LOLP} \le LOLP_t \le \overline{LOLP} \qquad \forall t \in T \tag{4-4}$$

$$n_{jt} \ge 0 \qquad \forall t \in T, \ j \in N \tag{4-5}$$

$$E_{jt} \ge 0 \qquad \forall t \in T, \ j \in N \tag{4-6}$$

$$s_{jt} \in \{0, \ 1\} \qquad \forall t \in T, \ j \in N_n \tag{4-7}$$

$$\mathbf{X} \in \Omega \tag{4-8}$$

where X is the solution vector, and Ω is the solution space. During the time period t: N_q is the units of generation type q, G_{qt} is equal to 1 if q type unit is constructed and 0 otherwise, and $\overline{G_{qt}}$ is the maximum. U_{jt} is the availability of unit j (%), D_t is the peak power demand during the period t (MW). $\underline{Gf_{jt}}$ and $\overline{Gf_{jt}}$ are the lower and upper bounds of annual utilization factor of the j type unit (%). $LOLP_t$ is the actual loss of load probability in this period with the bounds of $\underline{LOLP}$ and $\overline{LOLP}$. The formulation and calculation of $LOLP$ could also be found in [5].

METHODOLOGY

Considering the MOGEP optimization problem is a complex solution space, non-convex and nonlinear mixed integer objective functions, the tow-phase MOPSO method [6] is employed to solve the critical issue. This method can both obtain higher convergence rate and ensure better diversity of solutions.

A. The steps of two-phase MOPSO

Step 1: Initialize the parameters of two-phase MOPSO, including size of the swarm X, capacity of the archive Y, PSO coefficients w, c1 and c2, and maximum iterations Z, t=0;

Step 2: Randomly initialize the position and velocity of each particle in set X and set Y. Set the initial position as the individual best position µi of each particle;

Step 3: For t=1 to Z,

• Update archive,

• Select the global bests from Y for each particle in the set X based on the strategy of two-phase guided,

• Update position and velocity of every particle,

• If t<0.9Z, the particle is mutated according to the strategy,

• Each particle in set P has a new location, if the current location is dominated by its personal best location (μi), then the previous location is kept, otherwise, the current location is set as the personal best location. If the particles are mutually non-dominated, one particle is selected randomly,

• End.

B. MOGEP program flow

The major MOGEP modules and the general program flow are shown in Fig. 1. In these planning procedures, several possible planning solutions could be generated, and then a Fuzzy satisfying decision making approach was employed to get the optimal schemes, which has been depicted in [7].
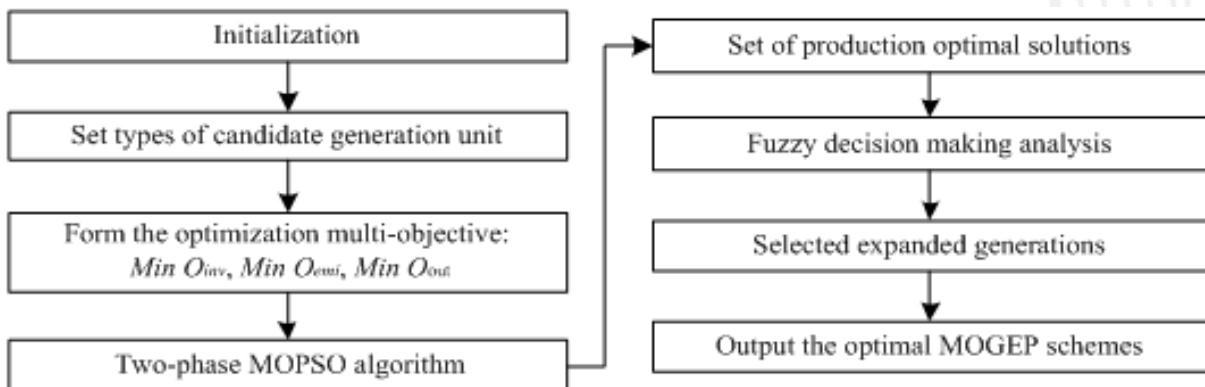

Fig. 1.   The MOGEP program flow

CASE STUDY

The relevant simulation of the proposed MOGEP framework has been carried out on a numerical test system in C++ software package, and the initial data is collected from [8]. The assumed 9-year planning horizon can be divided into three 3-year time periods. The generation technology options for capacity additions including nuclear, oil, coal, CCGT, and

wind. The predicted demand of each period is shown in Table I, and the technologies and costs data of the various types of existing and candidate units are illustrated in Table II and Table III, respectively.

Table I.   PREDICTED DEMAND OF EACH PERIOD

Period	P1	P2	P3
Peak (MW)	1400	1800	2100

Table II. EXISTING GENERATION TECHNOLOGIES AND COSTS

Technology	Capacity (MW)	Forced outage rate (%)	Fixed O&M (M$)	CO_2 Emission (t/MW)
Nuclear	600	10.0	234.00	0
Oil	350	6.0	20.13	0.743
Coal	200	8.0	85.82	0.834
CCGT	160	4.0	19.00	0.403

Table III. CANDIDATE GENERATION TECHNOLOGIES AND COSTS

Technology	Capacity (MW)	Forced outage rate (%)	Fixed O&M (M$)	CO_2 Emission (t/MW)	Capital cost/unit (M$)
Nuclear	1000	10.0	234.00	0	847.00
Oil	1200	6.0	20.13	0.743	80.57
Coal	800	6.5	85.82	0.834	179.00
CCGT	500	2.0	19.00	0.403	40.74
Wind	400	5.0	11.60	0	69.74

The discount rate is set to be 10%, the lower and upper bounds of LOLP are considered as 0.001 and 0.01, the value of wind energy production index is 10 $/MWh, the EENS cost is set at 50 $/MWh, and the forced outage rate for different technologies is ranged from 2% to 10%. Furthermore, the bounds of annual utilization factor for various technologies are assumed as 80%~90% (nuclear), 40%~70% (oil), 60%~80% (coal), 50%~70% (CCGT) and 20%~40% (wind), respectively.

The best three MOGEP planning schemes of this case study are presented in Table IV, it could be observed that Scheme 2 has the lowest total investment cost and lowest CO_2 emission amount, but with a notable outage cost. Further comparison between Scheme 1 and Scheme 3 shows that, Scheme1 is better than Scheme 3 due to its lower costs of

investment and energy outage, however, Scheme 3 has the lower value of CO2 emission on contrast with Scheme 2. In addition, both Scheme 2 and Scheme 3 could facilitate the maximum wind power to participate in expanding processes.

Table IV.   MOGEP SCHEMES OF THE SDTUDY CASE

Technology/ Objective	Scheme 1			Scheme 2			Scheme 3		
	P1	P2	P 3	P 1	P 2	P3	P 1	P2	P3
Nuclear (MW)	0	0	0	0	0	0	0	0	0
Oil (MW)	260	195	130	130	195	0	195	130	65
Coal (MW)	0	0	0	0	0	0	0	0	0
CCGT (MW)	140	210	280	280	210	280	210	280	210
Wind (MW)	100	100	50	100	100	200	100	100	200
O_{inv} (M$)	10624.69			10238.85			10789.31		
O_{emi} (t)	10019.23			9683.89			9817.16		
O_{out} (M$)	3.65			5.33			4.87		

CONCLUSION

A MOGEP approach considering large-scale wind generation integration is proposed in this paper, which optimizes three objectives simultaneously, i.e. the total investment cost, the amount of CO2 emission, and the outage cost. Accordingly, the two-phase MOPSO based solving algorithm is also introduced in this paper. The planning results of the numerical test system show that, for a large and practical system, the proposed MOGEP approach can effectively enhance the wind power installation in any arbitrary period during the preset horizon.

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