Multi-objective optimization configuration of wind-solar-storage microgrid based on NSGA-III

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Abstract. Reasonable allocation of the capacity of micro power supply such as wind turbine, photovoltaic and battery is the premise to ensure the economic, reliable and environmental protection operation of microgrid. Aiming at the capacity allocation problem of grid connected microgrid, this paper establishes a multi-objective optimal allocation mathematical model of grid connected microgrid considering the economy, reliability and environmental protection of microgrid, and uses the genetic algorithm NSGA-III based on the reference point selection mechanism to obtain the multi-objective Pareto solution set of micro source capacity allocation. The simulation results show that NSGA-III can not only optimize the three objective functions better than NSGA-II, but also improve the distribution uniformity of Pareto solution set and the diversity of population. The simulation results show that NSGA-III algorithm is more suitable for multi-objective optimal configuration of microgrid.

1. Introduction

The optimal configuration of microgrid needs to consider the maximum benefit of multi-objective coordination. In this regard, genetic algorithms are often used for analysis. The classical genetic algorithm NSGA-II algorithm [1] can select individuals who enter the offspring in the population through non-dominated sorting and crowding degree mechanism, but for 3 or more high-dimensional and complex multi-objective problems, the individual solutions selected only by the degree of crowding cannot be relatively evenly distributed in the solution space, and the result is easy to fall into the local optimum; while the NSGA-III algorithm [2] uses well-distributed reference points to maintain the diversity of the population, and can handle multi-objective high-dimensional problems well. At present, NSGA-III has been applied to the fields of image recognition [3] and ship stowage planning [4], but it has not been applied to the multi-objective optimization configuration of microgrid. In view of this, this paper applies the NSGA-III algorithm to the wind-solar-storage microgrid programming model to obtain a set of configuration plans, which provides a theoretical basis for decision-makers to choose a configuration plan.

2. NSGA-III algorithm

2.1. Reference point mechanism of NSGA-III algorithm

In the NSGA-III algorithm, widely distributed reference points are introduced to guide the search direction to maintain the diversity of the population \(S_i\). The reference point mechanism [5] is that the reference point is on the \((M-1)\)-dimensional hyperplane, and \(M\) is the number of objectives. Each objective is divided into \(H\) parts. The number of reference points \(P\) is:
2.2. Normalization of population individuals

The normalization of population individuals [2] steps are as follows:

Step 1 Define the ideal point. Find the minimum \( z_{i}^{\text{min}} \), \( i = 1, 2, \ldots, M \) of the population on each objective, then the constructed ideal point is \( (z_{1}^{\text{min}}, z_{2}^{\text{min}}, \ldots, z_{M}^{\text{min}}) \).

Step 2 Conversion of objective function. The formula is:

\[
f_{i}^{'}(x) = f_{i}(x) - z_{i}^{\text{min}}
\]

Step 3 Determine the extreme point of each objective. The formula is:

\[
z_{i,\text{max}} = \min(ASF(x, w')) = \min(\max(f_{j}^{'}(x)w_{j}')), x \in S_{i}
\]

In the formula, \( w' = (\tau, \ldots, \tau) \), \( \tau = 10^{-6} \), \( w' = 1 \).

Step 4 Calculate the intercept. Form an M-dimensional linear hyperplane. According to the general equation \( A_{1}x_{1} + A_{2}x_{2} + \cdots + A_{M}x_{M} = 1 \) of linear hyperplane, substitute the extreme point \( z_{i,\text{max}} \) to find the intercept \( a_{i}, i = 1, 2, \ldots, M \).

Step 5 Normalize the objective function. The normalization formula is:

\[
f_{i}^{*}(x) = [f_{i}^{'}(x) - z_{i}^{\text{min}}]/(a_{i} - z_{i}^{\text{min}})
\]

2.3. NSGA-III algorithm flow

The NSGA-III algorithm flow is as follows:

Step 1 Generate reference points according to a structured method, consider the number of objectives and equal scores in the objective direction, and calculate the reference point number.

Step 2 In the initialization process, a parent population \( P_{t} \) of size \( N \) is randomly generated.

Step 3 Use the simulation binary crossover and polynomial mutation [6] operation method to newly generate the progeny population \( Q_{t} \) of size \( N \).

Step 4 A new combined population \( R_{t} = P_{t} \cup Q_{t} \).

Step 5 Perform fast non-dominated sorting on the new combined population, use the reference point strategy to guide the search direction to select \( N \) individuals, and obtain a set of new population \( S_{t} \) close to the reference point.

Step 6 The algorithm runs to the maximum number of iterations and stops iterating. If terminated, repeat step 2~5.

3. Objective function model

In this paper, the economy, power supply reliability and renewable energy utilization efficiency of microgrid are considered, and three microgrid evaluation indexes are set up, including total equivalent annual cost, load loss rate and abandoned resource rate. The optimization variables are the number of photovoltaics, wind turbines, and batteries.

3.1. Total equivalent annual cost

Total equivalent annual cost is often used to measure the economics of microgrids. This objective function can be expressed as:

\[
\min C_{\text{eco}} = \min \left[ C_{\text{buy,grid}} + (C_{\text{act}} + C_{\text{com}} + C_{\text{dep}}) - C_{\text{sell,grid}} - C_{\text{sell,use}} \right]
\]
In the formula, \( C_{sell, \text{grid}} \) is the profit from selling electricity to the main network, \( C_{sell, \text{user}} \) is the profit from selling electricity to users, \( C_{buy, \text{grid}} \) is the cost of purchasing electricity from the grid, \( C_{aci} \) is the average annual investment cost, \( C_{aom} \) is the average annual operation and maintenance cost, \( C_{arp} \) is the average annual replacement cost. If \( C_{eco} \) is negative, it means that the microgrid project is profitable.

3.2. Load loss rate
Load loss rate reflects the reliability of microgrid. When the power is insufficient, we need to cut off part of the load to maintain energy balance. This objective function can be expressed as:

\[
\begin{align*}
\min p_l &= \min \left[ \sum_{t=1}^{T} (P_{\text{ele}, t}(\Delta t)) \right] / \sum_{t=1}^{T} (P_{\text{ele}}(t)\Delta t) \\
&= \min \left[ \sum_{t=1}^{T} (P_{\text{ele}}(t)\Delta t) \right] / \sum_{t=1}^{T} (P_{\text{ele}}(t)\Delta t) 
\end{align*}
\] (6)

In the formula, \( P_{\text{ele}, t}(t) \) represents the load power cut off at time \( t \), and \( P_{\text{ele}}(t) \) represents the total load demand at time \( t \). \( T \) is the number of hours per year.

3.3. Abandoned resource rate
When the wind and light resources are surplus, in order to meet the power balance, it is inevitable to abandon some resources. This objective function can be expressed as:

\[
\begin{align*}
\min r_a &= \min \left[ \sum_{t=1}^{T} (P_w(t)\Delta t) \right] / \sum_{t=1}^{T} [(P_{\text{wind}}(t) + P_{\text{PV}}(t))\Delta t]
\end{align*}
\] (7)

In the formula, \( P_{\text{wind}}(t) \) and \( P_{\text{PV}}(t) \) respectively represent the output of wind turbines and photovoltaics at time \( t \), which are determined by the local natural conditions at time \( t \). \( P_a(t) \) represents the abandoned power at time \( t \).

4. Constraint model

4.1. Power balance constraint

\[
P_{\text{wind}}(t) + P_{\text{PV}}(t) + P_{\text{B}}(t) = P_{\text{ele}}(t) + P_{\text{wind}}(t) + P_{\text{PV}}(t) 
\] (8)

In the formula, \( P_{\text{B}}(t) \) represents battery power (absorption is negative, output is positive), \( P_{\text{PV}}(t) \) represents the tie line power (the power delivered to the distribution network is positive).

4.2. Battery operation constraint
During the operation of the microgrid, in order to ensure the safety and service life of the battery, the charging and discharging power must satisfy the following relationship:

\[
P_{\text{C}, \text{max}}(t) \leq P_{\text{B}}(t) \leq P_{\text{D}, \text{max}}(t) 
\] (9)

\[
P_{\text{C}}(t) = \min \left[ P_{\text{C}, \text{max}}, \frac{E_t[SOC_{\text{max}} - SOC(t-1)]}{\Delta \eta_e} \right] 
\] (10)

\[
P_{\text{D}}(t) = \max \left[ P_{\text{D}, \text{max}}, \frac{\eta_e E_t[SOC(t-1) - SOC_{\text{min}}]}{\Delta t} \right] 
\] (11)
Among them, $SOC_{\text{min}}$ and $SOC_{\text{max}}$ are the lower and upper limits of the state of charge of the battery, respectively; $P_{\text{ch, max}}$ and $P_{\text{dis, max}}$ are the rated maximum charging power and discharge power of the battery pack, respectively; $\eta_c$ and $\eta_d$ are the battery charging and discharging efficiencies, respectively; $E_n$ is the rated capacity of the battery pack. During the optimization process, the battery's SOC operating range is set to 0.1-0.9, and the charging and discharging efficiency is 0.75.

4.3. Tie line maximum transmission power constraint

$$-P_{\text{mg, max}} \leq P_{\text{mg}}(t) \leq P_{\text{mg, max}}$$

In the formula, $P_{\text{mg, max}}$ is the maximum transmission power of the tie line.

4.4. Optimization variable constraint

$$0 \leq n_{PV} \leq n_{PV, \text{max}}, 0 \leq n_{WT} \leq n_{WT, \text{max}}, 0 \leq n_B \leq n_{B, \text{max}}$$

Among them, $n_{PV}$, $n_{WT}$ and $n_B$ are the number of photovoltaics, wind turbines, and batteries. $n_{PV, \text{max}}$, $n_{WT, \text{max}}$, and $n_{B, \text{max}}$ are the maximum installation quantities of photovoltaics, wind turbines, and storage batteries determined according to the actual site.

5. Experiments and Results

Taking the actual load in a certain area of Dalian, Liaoning Province as microgrid users, using local natural resource conditions, a grid-connected microgrid consisting of wind turbines, photovoltaics, and batteries will be built and put into operation. This paper uses HOMER to obtain the annual discrete value of wind, light resources and load, and use this as input for simulation analysis.

In the Matlab simulation environment, NSGA-III and NSGA-II are used to solve the multi-objective optimization configuration problem of microgrid respectively. Set the population size to 1000 and the maximum iteration number of the algorithm to 2000. After obtaining all the Pareto solution sets, select the solution that simultaneously satisfies the total equivalent annual cost of less than 0, the load loss rate is less than 3%, and the abandoned resource rate is less than 30%. Compare the performance of NSGA-III and NSGA-II. The results obtained are shown in figure 1 to figure 4.

![Figure 1. Pareto solution set after selection.](image1)

![Figure 2. Relationship between total equivalent annual cost and load loss rate](image2)
Figure 3 shows that the number of feasible solutions selected from the NSGA-III and NSGA-II solution sets are 165 and 60 respectively, which shows that it is easier to obtain a solution that meets the basic requirements through the NSGA-III algorithm.

From the distribution of any two objectives, we analyse the optimization ability of NSGA-III and NSGA-II algorithms for multi-objective optimal configuration of microgrid.

Figure 2 shows the relationship between the equivalent annual cost and the load loss rate. The mean total equivalent annual cost in the solutions of NSGA-III and NSGA-II are -719246 and -718917, respectively, with little difference. However, the mean load loss rate are 1.45% and 1.66%, respectively, indicating that NSGA-III has a greater improvement in the load loss rate. Moreover, from the distribution of these two objective functions, the solutions distribution of NSGA-III is more extensive.

Figure 3 shows the relationship between the equivalent annual cost and the abandoned resource rate. We can see most of the solutions of NSGA-III is under the solutions of NSGA-II. The average abandoned resource rate in the solutions of NSGA-III and NSGA-II are 8.41% and 17.73% respectively. It shows that NSGA-III can achieve lower abandoned resource rate under the same equivalent annual cost.

Figure 4 shows the relationship between the load loss rate and the abandoned resource rate. From the distribution, we can see most of the solution sets of NSGA-III are below the solution set of NSGA-II. The mean load loss rate of solutions of NSGA-III and NSGA-II are 1.45% and 1.86% respectively. The mean abandoned resource rate is 8.41% and 17.73%. It shows that the optimization result of NSGA-III for these two objective functions is obviously better than that of NSGA-II.

\[ Sp = \left(\frac{1}{n-1} \sum_{i=1}^{n} (\bar{d} - d_i)^2\right)^{1/2}, d_i = \min_j \left\{ \sum_{k=1}^{M} \left| f_k(x_i) - f_k(x_j) \right| \right\} \]  

(14)

In the formula, \( n \) is the number of feasible solutions in the Pareto front, \( d_i \) is the minimum sum of the difference between individual \( i \) and other individuals \( j \) in the corresponding objective dimensions, \( \bar{d} \) is the average of all \( d_i \), and \( M \) is the dimensions of objective function.
Figure 5 shows the $S_p$ value of each iteration. It can be seen from figure 5 that the value of NSGA-III is always smaller than the value of NSGA-II in the iterative process. After 2000 iterations, the mean $S_p$ values of the NSGA-III and NSGA-II are 4447 and 10632, respectively. It shows that NSGA-III can maintain population diversity better than NSGA-II.

6. Summary
In this paper, the NSGA-III algorithm is used to solve the Pareto solutions of the multi-objective optimal configuration of the grid-connected wind-solar-storage microgrid, and the capacity configuration scheme set under the condition of maximum comprehensive benefit is determined. It provides a theoretical basis and decision-making basis for improving the effectiveness of the configuration.

By comparing the results of NSGA-III and NSGA-II in solving this problem, we can know that the optimization ability of NSGA-III is stronger and can make the Pareto solution set distribution more uniform. Therefore, the NSGA-III algorithm is more applicable to the multi-objective optimization configuration problem of wind-solar-storage microgrid.

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