Optimal Planning Method for Distributed Wind/Solar/Battery Intergrated Microgrid

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Abstract. The high cost and randomness of intermittent renewable energy make the planning, integration and operation of power system more and more complicated. Therefore, determining the appropriate resource scale and related energy storage is the key to the efficient, economic and reliable operation of power system. In this study, two constraint based iterative search algorithms are proposed to optimize the scale of wind turbine (WT), solar photovoltaic (PV) and battery energy storage system (BESS) in microgrid connected configuration. The first algorithm is called resource size algorithm to determine the optimal size of resources; the second algorithm is called battery scale algorithm to determine the optimal capacity of BESS. These algorithms are mainly based on two key elements: maximum reliability and minimum cost. In this method, all possible solutions are searched in a given search space to avoid over and too small. At the same time, the forced outage rate of PV and the utilization rate of WT and Bess are considered to make it more practical. The simulation results show the effectiveness of the method.

1. Introduction

Renewable Energy (RE) is becoming an alternative to traditional fossil fuels because of its environmentally low-carbon and sustainable characteristics. Due to the gradual expansion of RE access scale in the power system, a microgrid (MG) consisting of distributed power supplies (e.g. PV, WT, etc.), BESS and electrical loads began to be formed in distribution networks, which has the ability to switch between two different modes of grid and off-grid to ensure its normal operation.

For renewable power sources (RESs) are less manageable than conventional generators, the existing RESs control research mainly maximizes the output power through advanced power electronic converters, but cannot achieve effective regulation of its output power [1]. BESS provides a solution to these problems by controlling BESS to store the excess power generation of RESs and release this part of the power during the required time period. It is worth noting that because of the high cost of
configuring RE and BESS in microgrids, effective capacity-setting methods are required to implement their commercial applications to ensure the normal operation of MG [2].

At present, more researchers have been working in the field of capacity optimization methods of PV, WT and BESS. Ref[3] optimizes the capacity of PV, WT and BESS in the system considering high reliability of power supply and minimizing cost. Ref [4], which targets cost, reliability and emissions, builds RE and BESS capacity optimization models and uses particle group optimization algorithms to solve them. Ref [5] is based on the minimization of the current total cost to achieve the fixed content of PV, WT, and BESS. The full-life cost of the equipment and CO2 emissions are taken into account in the literature [6], which solves the optimal capacity configuration of hybrid systems with PV, WT, diesel generator and BESS. However, in constructing the optimal PV, WT and BESS capacity configuration model of the system, the above literatures do not take into account the impact of the occurrence of PV and WT equipment forced shutdown due to uncertain natural factors on the reliability of the planning scheme.

Therefore, based on the above analysis, this paper proposes a joint planning method for the source storage of microgrid sources based on two constraint iteration algorithms. Firstly, on the basis of considering the forced blackout rate, the feasible search space for PV and WT configuration capacity is constructed, and then the optimal BESS configuration capacity under each feasible scheme is solved according to the cost, reliability and utilization of BESS, and finally the comprehensive reliability cost ratio determines the optimal PV, PV and BESS capacity configuration scheme in MG.

2. Source-storage joint planning model

2.1. DG capacity-setting method

The comprehensive model of MG using PV and WT to generate electricity is:

$$P_G^{i,j}(t) = N_{PV}^{i} P_{PV}(t) PV_{status}^{i}(t) + N_{WT}^{j} P_{WT}(t) WT_{status}^{j}(t) \quad \forall i \in [1, i_{max}], j \in [1, j_{max}], t > 0$$  \hspace{0.5cm} (1)

$$PV_{status}^{i}(t) = \begin{cases} 0 & G_{pv}^{i}(t) < FOR_{PV} \quad \forall t > 0 \\ 1 & \text{otherwise} \end{cases}$$  \hspace{0.5cm} (2)

$$WT_{status}^{j}(t) = \begin{cases} 0 & G_{wt}^{j}(t) < FOR_{WT} \quad \forall t > 0 \\ 1 & \text{otherwise} \end{cases}$$  \hspace{0.5cm} (3)

$$N_{PV}^{min} \leq N_{PV}^{i} \leq N_{PV}^{max}$$  \hspace{0.5cm} (4)

$$N_{WT}^{min} \leq N_{WT}^{j} \leq N_{WT}^{max}$$  \hspace{0.5cm} (5)

where $P_G$ is PV-WT hybrid power generation system, $N_{PV}$ and $N_{WT}$ is number of PV and WT, $P_{PV}$ and $P_{WT}$ are power generated by each PV and WT, $PV_{status}$ and $WT_{status}$ is work state of PV and WT.

$N_{PV}^{min}$, $N_{WT}^{min}$, $N_{PV}^{max}$ and $N_{WT}^{max}$ is the minimum and maximum number of PVs and WTs, using the following relational calculations:

$$N_{PV}^{min} = \frac{\sum_{i=1}^{n} \alpha P_{L}(t)}{\sum_{i=1}^{n} P_{PV}(t)}$$  \hspace{0.5cm} (6)

$$N_{WT}^{min} = \frac{\sum_{j=1}^{n} \beta P_{L}(t)}{\sum_{j=1}^{n} P_{WT}(t)}$$  \hspace{0.5cm} (7)

$$N_{PV}^{max} = \frac{\sum_{i=1}^{n} \gamma P_{L}(t)}{\sum_{i=1}^{n} P_{PV}(t)}$$  \hspace{0.5cm} (8)

$$N_{WT}^{max} = \frac{\sum_{j=1}^{n} \rho P_{L}(t)}{\sum_{j=1}^{n} P_{WT}(t)}$$  \hspace{0.5cm} (9)
where, \( \alpha, \beta, \gamma, \rho \) is scale factor, \( n \) is the total number, \( P_{pv} \) is PV output power, \( P_{wt} \) is WT output power.

The sum of the momentary errors between the load and the power generation, and the absolute values of all instantaneous errors are calculated below:

\[
\Delta p^{i,j}(t) = P_L(t) - P_G(t) \quad \forall t > 0
\]
\[
\Delta P^{i,j}(t) = \sum_{j=1}^{\text{max}} (|\Delta p^{i,j}(t)|) \quad \forall t > 0
\]

where \( \Delta p \) is a momentary error, \( \Delta P^{i,j} \) is the cumulative error corresponding to \( N_{pv} \) and \( N_{wt} \).

The smaller the cumulative error value, the more intermittent power generation effectively follows the load demand, and the greater the cumulative error value, the significant difference between the hybrid RE power generation and the load demand. Calculate the cumulative error of each possible combination of PV and WT and store it in a matrix as follows:

\[
\Delta P = \begin{bmatrix}
\Delta P^{(1,1)} & \ldots & \Delta P^{(1,\text{max})} \\
\Delta P^{(2,\text{max})} & \ldots & \Delta P^{(\text{max},\text{max})}
\end{bmatrix}
\]

The cumulative error values for each \( N_{pv} \) and \( N_{wt} \) are stored in the vectors \( N_{pv} \) and \( N_{wt} \), generating a search space:

\[
N_{pv} = \left[ \begin{array}{c} N_{pv}^{\text{min}} \\
K \\
N_{pv}^{\text{max}} \\
\vdots \\
N_{pv}^{(\text{min}+\text{z})}
\end{array} \right]
\]
\[
N_{wt} = \left[ \begin{array}{c} N_{wt}^{\text{min}} \\
K \\
N_{wt}^{\text{max}} \\
\vdots \\
N_{wt}^{(\text{min}+\text{z})}
\end{array} \right]
\]
\[
S_{\text{space}} = \left[ \begin{array}{c} 0 \\
N_{pv} \\
\vdots \\
N_{pv}^{(\text{min}+\text{z})}
\end{array} \right]
\]

Reduce \( S_{\text{space}} \) by selecting \( \Delta P \) the minimum value of each column:

\[
\Delta P_{\text{min}} = \left[ \begin{array}{c}
\Delta P_{\text{min}}^{(1,1)} \\
\ldots \\
\Delta P_{\text{min}}^{(1,\text{max})}
\end{array} \right]_{(z,\text{min})}
\]
\[
\Delta P_{\text{min}}^{(z,j)} = \text{min}(S_{\text{space}}(z, j)) \quad \forall j
\]
\[
z = 2, \ldots, \text{min}+1
\]

The \( N_{pv} \) and \( N_{wt} \) values for each \( \Delta P_{\text{min}} \):

\[
N_{pv_{\text{max}}} = \left[ \begin{array}{c} N_{pv_{\text{max}}}^{\text{min}} \\
L \\
N_{pv_{\text{max}}}^{(\text{min}+\text{z})}
\end{array} \right]
\]
\[
N_{wt_{\text{max}}} = \left[ \begin{array}{c} N_{wt_{\text{max}}}^{\text{min}} \\
L \\
N_{wt_{\text{max}}}^{(\text{min}+\text{z})}
\end{array} \right]
\]

Create a simplified search space \( RS_{\text{space}} \) based on \( \Delta P_{\text{min}}, N_{wt_{\text{max}}} \) and \( N_{pv_{\text{max}}} \):

\[
RS_{\text{space}} = \left[ \begin{array}{c}
\Delta P_{\text{max}}^{(1,1)} \\
\ldots \\
\Delta P_{\text{max}}^{(1,\text{max})}
\end{array} \right]
\]

2.2. BESS capacity-setting method

For the \( u \)th viable DG configuration scheme from \( RS_{\text{space}} \), the corresponding total output power should satisfy:

\[
\begin{align*}
\forall u \in [1, \text{min}], t > 0 \\
P_G(t) &= N_{pv_{\text{max}}} P_{pv_{\text{max}}}(t) + N_{wt_{\text{max}}} P_{wt_{\text{max}}}(t) \\
N_{pv_{\text{max}}} &\leq N_{pv_{\text{max}}}^{\text{min}} \\
N_{wt_{\text{max}}} &\leq N_{wt_{\text{max}}}^{\text{min}}
\end{align*}
\]

where \( P_G \) is output power of DG determined by \( RS_{\text{space}} \).

The difference between the generator’s active output and the load demand is:

\[
p_{pv_{\text{max}}}(t) = P_L(t) - P_G(t) \quad \forall u, t > 0
\]
The maximum installed capacity of energy storage is obtained by the following formula:

\[
P_{\text{max}}^u(h) = \begin{cases} 
  P_{\text{exp}}^u(h) & P_{\text{exp}}^u(h) > 0 \\
  0 & \text{otherwise}
\end{cases}
\]  

(23)

\[
P_{\text{max}}^u(h) = \sum_{i=1}^{n} P_{\text{exp}}^u(t)
\]

(24)

The maximum capacity constraint for the battery are expressed as:

\[
B_{\text{max}}^u = \max(p_{\text{exp}}^u)
\]

(25)

\[
B_{\text{cap}}^u(h) = \begin{cases} 
  B_{\text{exp}}^u & x = 1 \\
  CBS^u & x = 0
\end{cases}
\]

(26)

\[
B_{\text{max}} \text{ is the maximum capacity of BESS, } B_{\text{cap}} \text{ is the energy capacity required for BESS. If the battery is fully discharged, the condition is represented by } x=1; \text{ else, } x=0.
\]

The iteration area approximate algorithm is used to calculate CBS, given by the following equation:

\[
CBS^u(w) = \left( \min(w) + \max(w) \right) / 2
\]

(27)

\[
S_{\text{max}}^u(w + 1) = \begin{cases} 
  S_{\text{max}}^u(w) & x = 1 \\
  CBS(w) & x = 0
\end{cases}
\]

(28)

\[
S_{\text{max}}^u(w + 1) = \begin{cases} 
  S_{\text{max}}^u(w) & x = 0 \\
  CBS(w) & x = 1
\end{cases}
\]

(29)

\[
STEP^u_w = S_{\text{max}}^u(w) - S_{\text{max}}^u(w)
\]

(30)

where \(w\) is number if iterations.

The battery decision variable (BDV) is calculated as follows:

\[
BDV^u = \sum_{n} B_{\text{chg-dis}}^u(t) \quad \forall I > 0
\]

(31)

\[
B_{\text{chg-dis}}^u(t) = \begin{cases} 
  1 & |P_{\text{exp}}^u(t) - P_{\text{exp}}^u(t-1)| \geq \lambda P_{\text{max}}^u \\
  0 & \text{else}
\end{cases}
\]

(32)

where \(B_{\text{chg-dis}}\) is BESS charge-discharge factor, \(\lambda\) is a constant between 0 and 1.

Thus, the best energy capacity for BESS is calculated below:

\[
B_{\text{opt}}^u = \begin{cases} 
  B_{\text{exp}}^u & BDV^u \geq B_{\text{min}} \\
  CBS^u & \text{else}
\end{cases}
\]

(33)

BCS is determined by the following given regional reduction iteration algorithm:

\[
BCS^u(w) = \left( OCF_{\text{max}}^u(w) + OCF_{\text{min}}^u(w) \right) / 2
\]

(34)

\[
OCF_{\text{max}}^u(w + 1) = \begin{cases} 
  OCF_{\text{exp}}(w) & BDV^u \geq B_{\text{min}} \\
  CBS(w) & \text{else}
\end{cases}
\]

(35)

\[
OCF_{\text{min}}^u(w + 1) = \begin{cases} 
  BCS^u(w) & BDV^u \geq B_{\text{min}} \\
  OCF_{\text{exp}}(w) & \text{else}
\end{cases}
\]

(36)

\[
STEP^u_w = OCF_{\text{max}}^u(w) - OCF_{\text{min}}^u(w)
\]

(37)

where \(STEP\) is error, \(OCF_{\text{min}}\) is the lower boundary for the solution: \(OCF_{\text{max}}\) is upper boundary for solution.

This study is based on cost and reliability to determine the best solution. The total power generation after finding the appropriate BESS capacity for the combined number is calculated as follows:

\[
P_{\text{GT}}(t) = N_{\text{PV}}^{u} P_{\text{PV}}(t) + N_{\text{WT}}^{u} P_{\text{WT}}(t) + P_{\text{BES}}^u(t)
\]

(38)

where \(P_{\text{BES}}\) is power provided by BESS; \(P_{\text{GT}}\) is MG’s total power.

Reliability indicators, i.e. the energy of the load, are the total demand slots provided by the system during operation:
\[ E^u_\text{NS} = \sum_{i=1}^{n} G(t)^u \] (41)

\[ G(t)^u = \begin{cases} 
P_L(t) - P_{GT}^u & P_{GT}^u(t) < P_L(t) \\
0 & \text{otherwise}
\end{cases} \] (42)

Net discounted energy (NDE) could be calculated by present worth factor (PWF):

\[ PWF = \left(\frac{1 + d^j}{d} \right)^j \]

\[ NDE^J = E^J \times PWF \] (44)

where \( d \) is discount rate.

**Table 1.** Total operating cost of energy hub

| Type  | \( C_c \)/kW | \( C_{M(\text{Fixed})} \)/$/kWh/year | \( C_{M(\text{Variable})} \)/$/kWh/year | Life/year |
|-------|--------------|---------------------------------|---------------------------------|-----------|
| WT    | 2336         | 42                              | 0                               | 20        |
| PV    | 2023         | 14                              | 0                               | 20        |
| BESS  | 430          | 12                              | 0                               | 10        |

The sum of the initial investment cost \( C_c \), the operating maintenance cost \( C_{com} \), and the replacement cost \( C_{rep} \), including fixed and variable operating maintenance costs. The cost parameters for RESs and BESS are shown in Table 1.

\[ C^J = C^J_c + C^J_{com} + C^J_{rep} \] (45)

Thus, the optimal decision variables are defined as follows:

\[ ODV^J = E^J_c / C^J_c \] (46)

\[ SV = \left[ ODV^J \times K \times ODV^{\text{loss}} \right] \] (47)

3. **Case study**

The case study section first selects 1000 possible PV and WT combinations and calculates the BESS capacity, for each selected combination as shown in Figure 1.

![Figure 1. Capacity combinations](image1.png)

![Figure 2. Microgrid energy sources](image2.png)
Microgrid power generation with different SV values and electricity purchase from main grid is shown in Figure 2. With the increase of SV value, the generation in microgrid increases, while the electricity purchased from the main grid decreases, and finally both tend to be saturated. Since the study of the study is a grid-connected MG, when MG's output power is not sufficient to meet the load demand, MG buys power from the utility grid, so the entire system has high reliability.

Table 2. Different solutions.

|        | PV (MW) | WT (MW) | BES (MWh) | BES (MW) | MG (GWh) | Utility grid (GWh) | MG cost (c/kWh) | Total cost (c/kWh) | CO$_2$ (kt) |
|--------|---------|---------|-----------|----------|----------|-------------------|----------------|-------------------|-------------|
| Case 1 | —       | —       | —         | —        | 478.8    | —                 | —              | 10                | 527.77      |
| Case 2 | 82      | 100     | 53        | 17       | 268.9    | 210               | 15.91          | 13.32             | 231.65      |
| Case 3 | 57      | 187     | 63        | 20       | 339.3    | 139               | 18.73          | 16.18             | 153.33      |
| Case 4 | 40      | 250     | 94        | 30       | 369.8    | 109               | 21.11          | 18.58             | 120.24      |
| Case 5 | 10      | 650     | 133       | 43       | 422.8    | 56                | 41.67          | 37.96             | 61.73       |

Table 2 shows a comparison of unit costs, supplied clean energy and CO$_2$ emissions between different possible solutions. Case 1 means that all energy is provided by conventional power generation systems. In this case, the unit cost is the lowest and the emissions are the highest. In the rest, energy is provided by MG and utility grid. In the second case, the total cost is moderate and emissions are moderate. Compared to case 2, the percentage of clean energy provided by case 3 is higher than the percentage increase in total cost. In addition, CO$_2$ emissions have been reduced by a greater percentage than the percentage increase in cost. In the third case, CO$_2$ emissions are reduced by almost 70 percent compared to the first case. Case 5 has the lowest CO$_2$ emissions, and because of the higher installed capacity of RE and BESS, the unit cost has increased. Therefore, Case 3 is the best solution, because it provides a lot of clean energy at a reasonable unit cost and significantly reduces carbon dioxide emissions.

4. Conclusion

In this paper, a capacity optimization method for WT, PV and BESS in a grid-connected MG system is proposed. By comparing the cost and emission in several cases. By finding the optimal combination of all possible capacities of WT, PV and Bess, this method avoids the problems of insufficient capacity and excessive capacity, so the method is more practical.

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