A Grid-Connected Microgrid Optimal Allocation Method Considering Self-Balancing Rate

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Abstract. Microgrid optimal allocation is the primary problem that needs to be solved in the stage of microgrid planning and design. Whether the optimal allocation scheme is reasonable or not will directly determine the safe operation and economic benefits of microgrid. Unreasonable allocation scheme will lead to higher power supply costs and poor performance, and can not even reflect the inherent superiority of microgrid. In this paper, based on some indicators such as the self-balancing rate, the power fluctuation rate of the tie line, and the proportion of spontaneous self-use, the effect of the different operation strategies of the wind/light/storage grid-type microgrid is analyzed firstly. Then, an optimal allocation method for grid-connected microgrid is proposed. Furthermore, based on the economic scheduling operation strategy, considering the initial investment cost, replacement cost, operation maintenance cost, residual value and purchase electricity cost, the optimal allocation scheme with different self-balancing rate is compared.

1. Introduction

Microgrid optimal allocation is the primary problem that needs to be solved in the stage of microgrid planning and design. Whether the optimal allocation scheme is reasonable or not will directly determine the safe operation and economic benefits of microgrid. Unreasonable allocation scheme will lead to higher power supply costs and poor performance, and can not even reflect the inherent superiority of microgrid[1]. Grid-connected microgrids are connected to the power grid, which can provide some power support by the grid. The load ratio of grid-connected microgrids on its own reflects its power supply capacity and dependence on the grid[2].

For grid-connected microgrids, larger distributed generations (DGs) capacity can effectively improve local self-balancing capacity, and reduce the load ratio supplied by the grid. In the case of allowing power inversion, the rational use of battery energy storage system (BESS) can effectively realize the advantages of time-of-use electricity price[3]. On the other hand, due to the large cost of DGs and BESS investment, excessive capacity will directly affect the power supply economy of grid-connected microgrids, and will bring capacity-related operating and maintenance costs[4-5]. The economy and capacity allocation of grid-connected microgrids will vary depending on the self-balancing rate.
expectation level[6-7]. Considering various economic factors, it is worth discussing the optimal allocation scheme of grid-connected microgrid with different self-balancing.

Therefore, in the optimization of grid-connected microgrid allocation, besides economic indicators, it also need to fully evaluate its technical indicators to obtain a better performance of grid-connected microgrid. This paper proposes an optimal allocation method for grid-connected microgrid considering self-balancing rate, the power fluctuation rate of tie line, the spontaneous self-use ratio and other indicators. In the view of user benefit, the relationship between power supply capacity and power supply economy is analyzed.

2. Technology evaluation index

2.1. Self-balancing rate
The load ratio that depends on its own supply for a certain period of time for a grid-connected microgrid can be defined as the self-balancing rate, which can be expressed as:

\[ R_{self} = \frac{E_{self}}{E_{total}} \times 100\% = 1 - \frac{E_{grid-to-load}}{E_{total}} \times 100\% \]  (1)

where \( E_{self} \) is the energy supplied by the grid-connected microgrid itself, \( E_{grid-to-load} \) is the total energy flowing from the utility grid to the load, \( E_{total} \) is the total load demand.

The greater self-balancing rate of grid-connected microgrid is, the smaller the ratio of power supplied by utility grid. Different self-balancing rate expectation levels will affect the final capacity allocation scheme of grid-connected microgrids.

2.2. Spontaneous self-use rate
The proportion of microgrid load demand supplied by the DG output energy within a certain period of time is defined as a spontaneous self-use rate, which can reflect to some extent the utilization of grid-connected microgrids for their own power generation, which can be expressed as:

\[ R_p = \frac{E_{self}}{E_{ren}} \times 100\% \]  (2)

where \( E_{ren} \) is the total energy supplied by DGs in grid-connected microgrid.

3. Optimal allocation model

3.1. objective function
The objective function is to minimize the total cost in the whole life cycle:

\[ \text{Min} (f_1) \]  (3)

The total cost in life cycle includes cost value and residual value. The cost part includes initial investment, equipment renewal, operation and maintenance, and fuel cost. The total cost can be expressed as:

\[ f_1 = \sum_{k=1}^{K} \frac{C_k}{(1 + r)^k} - B_{salvage} \]  (4)

where \( K \) is the life of the microgrid, \( r \) is the discount rate, \( C_k \) is the cost for the \( k \)th year, \( B_{salvage} \) is the residual value of the device.

\( C_k \) can be calculated as follows:

\[ C_k = C_{I,k} + C_{R,k} + C_{M,k} + C_{F,k} \]  (5)
where \(C_{L,k}, C_{R,k}, C_{M,k}, C_{F,k}\) is the initial investment, renewal, maintenance, and fuel costs for the \(k\)th year, respectively.

\[
C_{L,k} = C_{\text{Battery}} + C_{\text{Ipv}} + C_{\text{Iwind}} + C_{\text{Igen}} + C_{\text{IConverter}}
\]

where \(C_{\text{Battery}}, C_{\text{Ipv}}, C_{\text{Iwind}}, C_{\text{Igen}}, C_{\text{IConverter}}\) is the investment costs for batteries, photovoltaic arrays, fans, diesel generators and bidirectional converters for batteries.

\[
C_{R,k} = C_{R_{\text{Battery},k}} + C_{R_{\text{Ipv},k}} + C_{R_{\text{Iwind},k}} + C_{R_{\text{Igen},k}} + C_{R_{\text{IConverter},k}}
\]

where \(C_{R_{\text{Battery},k}}, C_{R_{\text{Ipv},k}}, C_{R_{\text{Iwind},k}}, C_{R_{\text{Igen},k}}, C_{R_{\text{IConverter},k}}\) is the renewal costs of batteries, photovoltaic arrays, fans, diesel generators and bidirectional converters for batteries for the \(k\)th year.

\[
C_{M,k} = C_{M_{\text{Battery},k}} + C_{M_{\text{Ipv},k}} + C_{M_{\text{Iwind},k}} + C_{M_{\text{Igen},k}} + C_{M_{\text{Converter},k}}
\]

where \(C_{M_{\text{Battery},k}}, C_{M_{\text{Ipv},k}}, C_{M_{\text{Iwind},k}}, C_{M_{\text{Igen},k}}, C_{M_{\text{Converter},k}}\) is the maintenance costs of batteries, photovoltaic arrays, fans, diesel generators and bidirectional converters for batteries for the \(k\)th year.

### 3.2. Constraints

#### a) Power balance constraints:

\[
P_{\text{wt}} + P_{\text{pv}} + P_{\text{grid-in}} + P_{\text{discharge}} = P_{\text{load}} + P_{\text{charge}} + P_{\text{grid-out}}
\]

where \(P_{\text{wt}}, P_{\text{pv}}, P_{\text{grid-in}}, P_{\text{grid-out}}, P_{\text{charge}}, P_{\text{discharge}}, P_{\text{load}}\) is the active power of wind turbine, photovoltaic, utility-grid-to-microgrid, microgrid-to-utility-grid, battery charge, battery discharge and load.

#### b) Device power constraints: The output power of wind turbine and photovoltaic at a certain time should be less than the maximum theoretical output power determined by the installed capacity, wind speed and light intensity at that moment.

The power of the grid is constrained by a distribution transformer and can be expressed as:

\[
\begin{align*}
0 & \leq P_{\text{grid-in}} \leq f_{gi} P_{\text{grid-rate}} \\
0 & \leq P_{\text{grid-out}} \leq f_{go} P_{\text{grid-rate}} \\
f_{gi} + f_{go} & \leq 1
\end{align*}
\]

where \(P_{\text{grid-out}}\) is the power limits for the utility grid, \(f_{gi}, f_{go}\) is the indicator stakes for the input power of the utility grid and the power output to the grid, \(f_{gi}, f_{go}\) is a 0-1 variable.

The battery charge-discharge power constraint can be expressed as:

\[
\begin{align*}
0 & \leq P_{\text{charge}} \leq f_{bh} P_{\text{charge-max}} \\
0 & \leq P_{\text{discharge}} \leq f_{bo} P_{\text{discharge-max}} \\
f_{bh} + f_{bo} & \leq 1
\end{align*}
\]

where \(P_{\text{charge-max}}\) and \(P_{\text{discharge-max}}\) is the maximum charge and discharge power limits for the battery, \(f_{bh}, f_{bo}\) is the battery charge and discharge indicator stakes, \(f_{bh}, f_{bo}\) is a 0-1 variable.

#### c) Self-balancing rate constraints: In order to discuss the optimal allocation of the grid-connected microgrid at different self-balancing capacity, the self-balancing rate needs to be limited in different computing scenarios, which can be expressed as:

\[
R_{\text{low}} \leq R_{\text{self}} \leq R_{\text{high}}
\]

where \(R_{\text{low}}\) is the lower limit of the self-balancing rate, \(R_{\text{high}}\) is the upper limit of the self-balancing rate.
4. Solving algorithm
Genetic algorithm (GA) and mixed integer programming software (CPLEX) are used to solve the problem. GA algorithm is used in the outer layer to optimize the capacity configuration scheme of the grid-connected microgrid based on the set optimization objectives. The mixed integer programming software is used in the inner layer to find the optimal operation scheme under the corresponding capacity allocation with the minimum power supply cost in each dispatching cycle (such as 24 h) within the simulation time (such as 1 year). The results of the optimal operation scheme obtained from the inner layer are returned to the outer layer. The outer layer algorithm calculates the optimization target value according to the capacity allocation information and the optimal operation scheme results, and optimizes through genetic operation, and finally obtains the optimal solution.

5. Case study
The proposed method is used to analyse the optimal allocation of a grid-connected microgrid. The alternative power sources are wind turbine, photovoltaic and battery, and their specifications, purchase costs and annual operation and maintenance costs are shown in Table 1. The time of use price is adopted for power purchase and sale of users, and the price parameters are shown in Table 2.

| Table 1. Parameters of alternative power supply |
|-----------------------------------------------|
| name          | specifications | purchase costs | annual operation and maintenance costs |
|----------------|----------------|----------------|----------------------------------------|
| wind turbine   | 10kW           | 55,000 RMB/unit | 1000 RMB/unit                          |
| photovoltaic   | /              | 6000 RMB/kW     | 20RMB/kW                               |
| battery        | 2V/1000Ah      | 1500 RMB/piece  | 5 RMB/piece                            |

| Table 2. Time-of-use electricity price parameters |
|-----------------------------------------------|
| Time                         | Purchasing electricity (RMB/kWh) | Selling electricity (RMB/kWh) |
|-----------------------------|----------------------------------|-------------------------------|
| 00:00-08:00                 | 0.37                             | 0.28                          |
| 08:00-12:00, 17:00-21:00    | 0.87                             | 0.72                          |
| 12:00-17:00, 21:00-24:00    | 0.69                             | 0.53                          |

Taking the monthly typical wind speed, irradiance and load (working days and rest days) data as input, the annual total power consumption is about 1.29 million kWh. According to the time of use price, under the condition that the load is completely supplied by the utility grid, the annual electricity purchase cost of consumers is about 1.188 million yuan.

Calculation parameter settings are shown in Table 3. In order to explore the optimal allocation scheme in a large capacity range, the upper limit value of wind / light / storage capacity is set broadly.

| Table 3. Calculation parameter |
|--------------------------------|
| name          | value          |
|----------------|----------------|
| GA             |                |
| population size| 100            |
| genetic algebra| 20             |
| Simulation parameters |        |
| simulation duration | 24*24 h       |
| simulation step | 1 h            |
| $N_{wt-min}$   | 0              |
| $N_{wt-max}$   | 20             |
| $N_{pv-min}$   | 0              |
| $N_{pv-max}$   | 1000           |
| $N_{es-min}$   | 0              |
| $N_{es-max}$   | 2000           |
Constraint parameters

\[
\begin{align*}
S_{\text{min}} & = 0.4 \\
S_{\text{max}} & = 0.95 \\
\lambda_{\text{out}} & = 0.35 \\
S_{f} & = 0.2 \\
S_{i} & = 1.5 \\
P_{\text{grid-rate}} & = 500 \text{ kW} \\
\text{Limp} & = 50 \text{ kW} \\
T & = 1 \text{ h}
\end{align*}
\]

5.1 Results

The optimization calculations for the different self-balancing ranges are shown in Table 4 and Figure 1.

Table 4. Results of simulation

| Number | \( R_{\text{low}} \) /% | \( R_{\text{high}} \) /% | WT / kW | PV / kW | Number of batteries | \( R_{\text{self}} \) /% | \( C_{\text{total-eav}} \) / ten thousand RMB |
|--------|----------------|----------------|--------|--------|-------------------|----------------|------------------|
| 1      | 0              | 10             | 0      | 40     | 350               | 2.9            | 134.7            |
| 2      | 10             | 20             | 0      | 210    | 340               | 15.2           | 138.9            |
| 3      | 20             | 30             | 0      | 420    | 350               | 29.2           | 134.7            |
| 4      | 30             | 40             | 0      | 540    | 430               | 35.8           | 127.5            |
| 5      | 40             | 50             | 0      | 650    | 530               | 40.5           | 135.9            |
| 6      | 50             | 60             | 2      | 990    | 860               | 50.1           | 149.1            |
| 7      | 60             | 70             | /      | /      | /                 | /              | /                |

Figure 1. Simulation results of different self-balancing rate.

The calculation results in Table 4 are the optimal economic allocation scheme within the corresponding self-balancing rate range. When the self-balancing rate range is 60% - 70%, there is no allocation scheme meeting the constraint condition within the set capacity range. It can be seen from Table 4 that the power supply economy of grid-connected microgrid is different under different expected levels of self-balancing rate. Increasing the wind / solar / storage capacity can effectively improve the local self-balancing capacity. Due to the poor local wind resources, the number of wind turbines obtained in the scheme is almost zero, which indicates that the photovoltaic installed capacity should be preferentially increased if the actual conditions permit.

On the other hand, increasing the wind / solar / storage capacity in a certain range can also improve the power supply economy of the grid connected microgrid. It can be seen from Table 4 and Figure 1 that the \( C_{\text{total-eav}} \) values in scheme 1 and scheme 3 are equal. The increase of wind / solar / storage capacity
does not cause the increase of $C_{\text{total-eav}}$, and scheme 3 effectively improves the local self-balancing ability. When the self-balancing rate is 35.8%, the power supply economy of the system is optimal. If the wind / solar / storage capacity is continuously increased, the self-balancing ability will be improved, but it needs to pay a large economic cost. When the self-balancing rate increases from 35.8% to 50.1%, $C_{\text{total-eav}}$ increases by 16.9%. On the whole, the curve in Figure 1 shows a "V" shape. Too low or too high expected level of self-balancing rate will affect the power supply economy of grid-connected microgrid to a certain extent. The curve trend in Figure 1 is obtained based on the setting of this case. For other specific cases, the above method can be used for calculation and analysis, so as to obtain the curve trend with reference significance for the optimal allocation decision.

6. Conclusions

In this paper, an optimal allocation method considering the index of self-balance rate is proposed. The relationship and influence between power supply capacity and power supply economy is analyzed, which from the perspective of user benefits. When using this method to optimize the allocation of grid-connected microgrid, not only the economic indicators are considered, but also comprehensively evaluate other technical indicators. The optimal scheme based on the operation performance of grid-connected microgrid can be obtained, which can provide reference for guiding the optimal allocation of grid-connected microgrid.

References

[1] Q. Wei, D. Liu, F. L. Lewis, et al. Mixed Iterative Adaptive Dynamic Programming for Optimal Battery Energy Control in Smart Residential Microgrids[J]. in IEEE Transactions on Industrial Electronics, 2017,64(5): 4110-4120.

[2] Zhao H, Hu E, Wang Z, et al. Optimal Configuration of Grid Connected Microgrid Considering CCHP and Analysis of Energy Saving and Emission Reduction[C]. 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing China, 2018,1-9.

[3] U. T. Salman, F. S. Al-Ismail and M. Khalid. Optimal Sizing of Battery Energy Storage for Grid-Connected and Isolated Wind-Penetrated Microgrid[J]. in IEEE Access, 2020,8(5):91129-91138.

[4] U. Akram, M. Khalid and S. Shafiq. Optimal sizing of a wind/solar/battery hybrid grid-connected microgrid system[J]. in IET Renewable Power Generation, 2018,12(1): 72-80.

[5] J.P. Ram, T.S. Babu and N. Rajasekar. A comprehensive review on solar PV maximum power point tracking techniques[J]. Renew. Sustain. Energy Reviews, 2017, 67(1): 826-847.

[6] A. C. Luna et al. Generation and demand scheduling for a grid-connected hybrid microgrid considering price-based incentives[C]. IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing China, 2017, 2498-2503.

[7] M. Pereira, D. Limon, L. Valverde, et al. Periodic Economic Control of a Nonisolated Microgrid[J]. in IEEE Transactions on Industrial Electronics, 2015, 62(8):5247-5255.