Comparison of centralised and distributed energy storage configuration for AC/DC hybrid microgrid

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Abstract: Based on the analysis of cost, benefit and reliability of energy storage system, the capacity allocation in AC/DC hybrid microgrid is compared. The cost of energy storage system and the possible benefits are analysed in detail. Through the calculation of islanding operation time of power supply system with distributed generators and energy storage, and combined with the Monte Carlo simulation, the reliability parameters are calculated. Based on the comparative analysis, applicable scenarios of centralised storage and distributed storage are obtained.

1 Introduction

Nowadays, power system is facing the dual pressures of traditional energy resources shortage and environmental pollution. Developing renewable energy and reducing emissions are the key to solve this problem [1]. Due to the remarkable difference in the power generation characteristics of different new energy sources, the rapid development of microgrid has been achieved in order to overcome the great challenge to the stable operation of the traditional grid with the increase of the new energy penetration in the distribution network [2, 3]. Single AC microgrid or DC microgrid has some limitations in connecting different AC and DC power generation devices, energy storage and loads. AC/DC hybrid microgrid combines advantages of AC microgrid and DC microgrid technology, using VSC DC and AC/DC hybrid distribution network technology, reduce economic losses caused by conversion of the single AC microgrid or DC microgrid, and improve the flexibility of the control system [4]. However because of the volatility of output power of renewable energy and load, a certain amount of energy storage is needed to stabilise the fluctuation in microgrid. According to the different configuration methods of energy storage, the energy storage configuration can be divided into centralised and distributed, and each of these two methods has its advantages and disadvantages.

At present, many studies focus on the optimal allocation of the centralised storage. Suhua et al. [5] proposed planning model of battery storage capacity based on the prediction model of variable life battery energy storage. Reference [6, 7] optimised the capacity of battery storage in microgrid by ensuring stable frequency and economical efficiency using particle swarm algorithm, as well as considering the demand of the system response. Huishi et al. [8] considered SOC and efficiency of energy storage system, and optimised the capacity of hybrid energy storage with maximum voltage of tie line in microgrid as the goal. Peng et al. [9] determined the storage capacity using the methods of probability from the perspective of inertia response of the system. Suhua et al. [10] introduced the energy buffer system by considering the volatility of wind power, and optimised energy storage capacity according to the economic benefits. A few research the optimal allocation of distributed storage. The literatures [11, 12] proposed a bi-level optimisation model to determine the location and capacity of energy storage. Singh et al. [13] established the locating and sizing model of energy storage with the objective of minimum voltage fluctuation of system, load fluctuation and energy storage capacity, and used improved particle swarm optimisation algorithm to solve this model. Qiong et al. [14] added the current protection to constraints, established locating and sizing model of energy storage, and designed a hybrid algorithm to solve the model according to the characteristics of distribution network fault with energy storage station.

In the existing researches, there is very little comparison between different methods of energy storage configurations in microgrid. In view of the lack of existing research, according to the economy and reliability of the system, the two types of energy storage configuration are compared. At first, the cost of energy storage system and the possible benefits are analysed in detail. Through calculating the islanding operation time of power supply system with distributed generators and energy storage, the reliability parameters are calculated combined with the Monte Carlo simulation. Finally, based on the comparative analysis, applicable scenarios of centralised storage and distributed storage are obtained.

2 Similarities and differences between centralised energy storage and distributed energy storage

2.1 Similarities between centralised energy storage and distributed energy storage

In AC/DC hybrid microgrid, either centralised storage or distributed storage can be used for peak-load shifting, standby power supply, peak modulation and frequency modulation. They can stabilise internal imbalance of the microgrid, as well as balance imbalanced power between sub-microgrid.

2.2 Differences between centralised energy storage and distributed energy storage

(i) Configuration location: Centralised energy storage is usually fixed on the DC side of interconnected converter of AC and DC microgrids or DC microgrid, while distributed energy storage can be dispersed in the system, except for the balanced nodes.

(ii) Energy storage capacity: When the energy storage capacity is optimised, the minimum total energy storage capacity or the minimum total cost is usually as the optimisation target. As
the operating costs of the two energy storage configurations are inconsistent, the optimal total energy storage capacity is usually not the same.

(iii) Effect: Due to different function process of the two energy storage configurations, the benefits of centralised energy storage and distributed energy systems are different.

(iv) The difficulty of control: Centralised energy storage is easy to control at one location, while distributed energy storage is dispersed at different location points, and the difficulty of control is obviously increased.

3 Cost-benefit model

3.1 Cost model

(i) Construction cost: The construction cost of the energy storage system, besides the cost of the energy storage itself, includes the cost of the converter connected to the energy storage and microgrid system, so the construction cost can be expressed as

\[ C_{ch} = c_{ch} \sum_{j=1}^{N} E_{j} + c_{c} \sum_{j=1}^{N} x_{i} n_{i} \frac{e(1+e)^{Y_{i}}}{(1+e)^{b}-1} \]  

where \( c_{ch} \) and \( c_{c} \) are, respectively, construction cost of unit energy storage capacity and unit cost of converter; \( E_{j} \) is energy storage capacity installed in the node \( j \); \( x_{i} \) is a 0–1 variable, 1 indicates that node \( i \) exists converter of energy storage configuration, 0 indicates node \( j \) does not exist it; \( n_{i,j} \) is the number of energy storage converter at the node \( i \); \( e \) is discount rate; \( Y_{i} \) is the operating life of an energy storage system; \( N \) is number of nodes in the system.

(ii) Operation and maintenance cost: The operation and maintenance cost of the energy storage system \( C_{M} \) includes the cost of charging and discharging of the energy storage system, and the processing cost of the waste battery

\[ C_{M} = \sum_{d=1}^{365} \sum_{t=1}^{24} \left( c_{om} \sum_{j=1}^{N} P_{dch}^{bch} + c_{om} \sum_{j=1}^{N} P_{dch}^{dis} \right) \]  

\[ + c_{om} \sum_{j=1}^{N} P_{loss} + c_{om} \sum_{j=1}^{N} E_{j} \]  

\[ \sum_{d=1}^{365} \sum_{t=1}^{24} \left( c_{om} \sum_{j=1}^{N} P_{dch}^{bch} + c_{om} \sum_{j=1}^{N} P_{dch}^{dis} \right) \]  

\[ + c_{om} \sum_{j=1}^{N} P_{loss} + c_{om} \sum_{j=1}^{N} E_{j} \]  

where \( c_{om} \) and \( c_{om} \) are, respectively, unit operational cost of energy storage system and transporting electric energy; \( P_{dch}^{bch} \) and \( P_{dch}^{dis} \) are, respectively, charging and discharging power of the node \( j \) on the \( d \)th day during the period of \( t \).

(iii) Power shortage cost: Under the requirement of certain power supply reliability, the system may cause economic losses due to power shortage. There are many factors that affect the cost of power shortage, including the time of power shortage, the power shortage, the duration of power shortage, the frequency of power shortage and the type of users. The annual power shortage cost can be calculated as follows:

\[ C_{PS} = \sum_{i=1}^{n} \sum_{j=1}^{m} \left( k_{ps} P_{j} + k_{be} E_{ij} \right) \]

where, \( k_{ps} \) and \( k_{be} \) are, respectively, loss factor of unit power shortage and unit loss of the node \( i \), the value is related to the type of users of the node; \( P_{j} \) and \( E_{ij} \) are, respectively, power and quantity of the node \( i \) under the \( j \)th power shortage.

3.2 Benefit model

Referring to the five categories of energy storage revenue which the Sandia laboratory research pointed out [15], we not only consider the benefits of the grid due to energy storage, but also consider the benefits of the user due to energy storage. In this paper, the benefits of energy storage system are divided into electricity benefit, benefit of reliable power supply, benefit of improving power quality, operation benefit and environmental protection benefit.

(i) Electricity benefit: The ‘filling valley’ of the energy storage system can effectively raise the trough load and enable the microgrid to accept more wind power and photovoltaic. The electricity of more wind and photovoltaic that energy storage system allows the microgrid to admit is as follows:

\[ E_{WRPC} = \sum_{i=1}^{365} \int_{t_{1}}^{t_{2}} \left( \Delta P_{w}(t) + \Delta P_{PV}(t) \right) dt \]  

\[ \Delta P_{w}(t) + \Delta P_{PV}(t) = \begin{cases} 0, & P_{w}(t) + P_{PV}(t) \leq P_{L}(t) \\ P_{w}(t) + P_{PV}(t) - P_{L}(t), & P_{L}(t) < P_{w}(t) + P_{PV}(t) \end{cases} \]

\[ \Delta P_{w}(t) + \Delta P_{PV}(t) = \begin{cases} \Delta P_{w}(t) + \Delta P_{PV}(t) - P_{L}(t), & P_{L}(t) \leq \Delta P_{w}(t) + \Delta P_{PV}(t) \end{cases} \]

where \( \Delta P_{w}(t) \) and \( \Delta P_{PV}(t) \) are, respectively, the power of more wind and photovoltaic that energy storage system allows the microgrid to admit; \( t_{1} \) and \( t_{2} \) are, respectively, the time for starting and finishing; \( P_{w}(t) \), \( P_{PV}(t) \), and \( P_{L}(t) \) are, respectively, power of wind, photovoltaic and load.

Therefore, electricity benefit is as follows:

\[ B_{E} = c_{WRPC} E_{WRPC} \]

\[ B_{E} = c_{WRPC} E_{WRPC} \]

\[ \text{where} \ c_{WRPC} \text{is average price of wind power and photovoltaic.} \]

(ii) Benefit of reliable power supply: Since it is difficult to estimate the benefit of a certain power supply reliability level, to simplify calculation, the cost of power supply is used to reflect the reliable benefit of power supply, that is, the economic losses caused by the power shortage due to insufficient power supply. The power supply is reliable and the benefit is the difference between the shortage cost before the energy storage configuration and the shortage cost after the energy storage configuration:

\[ B_{RPS} = \Delta C_{PS} = C_{PS} - C_{PS}^{*} \]

\[ \text{where} \ C_{PS} \text{is the shortage cost after the energy storage configuration.} \]

(iii) Benefit of improving power quality: First of all, the power quality before and after energy storage configuration should be evaluated. Then, the various power qualities need to be translated into one kind of power quality index, and loss cost caused by the problem of power quality can be calculated. After, according to the loss cost before and after energy storage configuration, benefit of improving power quality can be calculated. Therefore, the benefit of improving power quality can be expressed as follows:

\[ B_{PQ} = \Delta C_{PQ} = C_{PQ} - C_{PQ}^{*} \]

\[ \text{where} \ C_{PQ} \text{is the loss cost after energy storage configuration.} \]

(iv) Operation benefit: The energy storage system reduces power consumption through charging during the trough and discharging during the peak. Thus, the electricity benefits (yuan/year) is electricity cost reduction due to time-of-use price in the ‘charging during the trough and discharging during the peak’ operation mode of energy storage system, which can
be expressed as follows:

\[ B_{sp} = c_e W_{W&PV} + \left( \sum_{i=1}^{w} c_{metal,i} \right) \beta_{ES} E_{ES} \]

where, \( c_e \) is unit emission costs during power generation of thermal power unit; \( c_{metal,i} \) is unit cost of metal \( i \); \( \theta_i \) is the amount of metal \( i \) in a unit weight of storage battery; \( \beta_{ES} \) is energy to weight ratio of energy storage.

4 Reliability evaluation model

The configuration of energy storage will increase the confidence capacity of distributed generation of the load point, and then enhance the reliability of the system. As the microgrid is in the islanding operation mode, when the output power of distributed generation is greater than the load demand, the energy storage absorbs energy; when the output power of the distributed generation is less than the load demand, the energy storage can release energy. However the reliability is limited by the energy storage capacity at the same time. In the power supply system combined distributed power supply with energy storage, when the energy storage is unable to output, and there is no other stable power supply, the system will stop working. In this paper, the reliability of AC/DC hybrid microgrid is calculated to evaluate its system reliability. According to the fault rate of the components, fault time of system can be calculated. Then, the power supply time of microgrid with energy storage in islanding operation mode can be calculated. According to the fault time and power supply time, the interruption duration can be obtained. After, according to the interruption duration and the times of power interruptions of each load, the reliability index of each load point can be calculated, furthermore, the reliability index system can be obtained.

The specific steps to calculate the reliability index of microgrid are as follows [17]:

(i) The failure time of all components is calculated by Monte Carlo simulation

\[ T^{\alpha}_{\text{fault}} = -\left(1/\mu_i\right) \ln \nu \]

where \( \mu_i \) is repair rate of component; \( \nu \) is a random number obeying uniform distribution from the interval \((0,1)\).

(ii) Through integrating the running time sequence of all components, all the fault events in the system are obtained at simulation time. To statistic the load affected by each fault, these loads are divided into direct interruption load, load that can be transferred for restoration and self-powered load.

(iii) For the direct interruption load \( \nu \), the interruption duration of load is duration of the fault, total interruption duration of the load point is \( T_{pf} = T_{pf} + T_{\text{fault}} \), where \( T_{\text{fault}} \) is the duration of the \( k \)th fault, the times of power interruptions is \( N_{pf} + \cdot \).

For the self-powered load \( v \), the interruption duration of load is related to power supply duration of islanding system caused by the fault. If \( T_{\text{island}} < T_{\text{fault}} \), the interruption duration of load is the duration from the time energy storage is depleted to the time load restore power, the times of power interruptions is \( N_{pf} + \cdot \).

(v) Environmental protection benefit: The environmental benefits [16] of energy storage system include emission reduction benefits of the power grid with energy storage system (assuming that the main grid supplies power generated by thermal power units), and benefit of recovery of metal material gained from waste batteries. Thus, environmental protection benefit can be expressed as follows:

\[ B_{env} = E_{storage} - E_{em} \]

where, \( E_{storage} \) is amount of energy storage in a unit weight of storage battery; \( E_{em} \) is unit emission costs during power generation of thermal power unit; \( \theta_i \) is the amount of metal \( i \) in a unit weight of storage battery; \( \beta_{ES} \) is energy to weight ratio of energy storage.

5 Simulation results

Through the comparative analysis of several scenarios, this paper illustrates applicable scenarios of different methods of energy storage configuration, and the specific scenarios is shown in Table 1. Small-scale microgrid is benchmark low voltage microgrid system [18], large-scale microgrid is the microgrid system of reference [19]. We remove the energy storage configuration of original system, and re-plan position and capacity of storage energy. The three structures of the AC/DC hybrid microgrid are shown in Fig. 1. For each sub-microgrid, the line and load parameters are

| Scenario | Scale of sub-microgrid | Number of sub-microgrid | Composition of sub-microgrid |
|----------|------------------------|--------------------------|-------------------------------|
| 1        | small                  | 2                        | 1 AC + 1 DC                  |
| 2        | large                  | 2                        | 1 AC + 1 DC                  |
| 3        | small                  | 3                        | 2 AC + 1 DC                  |
| 4        | small                  | 3                        | 1 AC + 2 DC                  |

![Fig. 1 Structure of AC/DC hybrid microgrid](image-url)

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referred to the literature [18, 19]. Sodium sulfur battery is used to be energy storage, its unit capacity investment cost is 3000 yuan/(kW h), and unit operation cost of energy storage is 0.009 yuan/(kW h) [20].

Under different reliability requirements, capacity and location of energy storage in hybrid microgrid are optimised according to the economy. The position of centralised energy storage is fixed on the DC side of the converter between the AC and DC network. Under reliability requirements of the average failure rate of 0.1, the energy storage configuration results are optimised with the objective of the maximum gain of energy storage system, and the specific results are shown in Table 2.

Through the observation on Table 2, the construction cost of centralised energy storage is lower than that of distributed energy storage, but the operation and maintenance cost is higher. As the centralised energy storage can be used to compensate unbalanced power of multiple nodes, the total capacity is smaller than distributed, but the distance between the energy and load is far, which causes a great loss of network. Compared to net gain of 4 cases, scenario 1 with centralised energy storage is more benefit, the scenario 2 with distributed energy storage is more profitable. Therefore, centralised energy storage is suitable to small-scale hybrid microgrid system, and distributed energy storage is suitable to large-scale hybrid microgrid system.

Compared to net income of 4 cases on Table 3, the scenario 3 with centralised storage configuration is more benefit, scenario 4 with distributed energy storage is more profitable. Since the DC system of scenario 4 is bigger than that of scenario 3, and the converter number of the energy storage system is few, difference of construction cost between centralised and distributed energy storage system is small. Therefore, the centralised energy storage is applicable to the hybrid microgrid system with small DC system, and the distributed energy storage is applicable to the hybrid microgrid system with large DC system.

Cost-benefit comparison of scenario 1 under different reliability requirements with different configuration of centralised storage is shown in Fig. 2. It can be observed that the cost, benefit and net gain of energy storage decrease with increasing failure rate, and the amplitude of reduction is little.

Net gain comparison of scenario 1 under different reliability requirements with different energy storage configuration is shown in Fig. 3. It can be observed that the reduction amplitude of net gain of distributed energy storage is larger than that of centralised energy storage. As the average failure rate is low, the net gain of

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Table 2 Economic comparison of different energy storage configurations under scenario 1 and scenario 2

| Scenario | Configuration method of ESS | Total ESS capacity, kW h | Construction cost, yuan | Operation cost, yuan | Power shortage, cost/yuan | Benefit/yuan | Net gain/yuan |
|----------|-----------------------------|--------------------------|-------------------------|---------------------|--------------------------|-------------|--------------|
| 1        | centralised                 | 103                      | 3.09 × 10^5             | 200.9               | 100.89                   | 5.06 × 10^5 | 1.97 × 10^5  |
| 1        | distributed                 | 109                      | 3.27 × 10^5             | 89.3                | 89.17                    | 5.08 × 10^5 | 1.81 × 10^5  |
| 2        | centralised                 | 470                      | 1.41 × 10^6             | 857.61              | 278.14                   | 2.16 × 10^6 | 7.50 × 10^5  |
| 2        | distributed                 | 512                      | 1.54 × 10^6             | 521.23              | 214.18                   | 2.60 × 10^6 | 1.07 × 10^6  |

Table 3 Economic comparison of different energy storage configurations under scenario 3 and scenario 4

| Scenario | Configuration method of ESS | Total ESS capacity, kW h | Construction cost, yuan | Operation cost, yuan | Power shortage, cost/yuan | Benefit/yuan | Net gain/yuan |
|----------|-----------------------------|--------------------------|-------------------------|---------------------|--------------------------|-------------|--------------|
| 3        | centralised                 | 277                      | 9.31 × 10^5             | 300.9               | 146.81                   | 1.47 × 10^6 | 5.35 × 10^5  |
| 3        | distributed                 | 309                      | 1.07 × 10^6             | 169.1               | 102.22                   | 1.49 × 10^6 | 4.18 × 10^5  |
| 4        | centralised                 | 296                      | 9.98 × 10^6             | 257.61              | 133.45                   | 1.50 × 10^6 | 5.03 × 10^5  |
| 4        | distributed                 | 321                      | 1.02 × 10^7             | 121.23              | 114.56                   | 1.53 × 10^6 | 5.04 × 10^5  |

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Fig. 2 Structure of AC/DC hybrid microgrid

Fig. 3 Structure of AC/DC hybrid microgrid
distributed energy storage is larger than that of the centralised; and as the average failure rate is high, net gain of distributed energy storage is less than that of the centralised. Therefore, centralised energy storage is suitable for hybrid microgrid with low reliability, and distributed energy storage is applicable to hybrid microgrid with high reliability.

6 Conclusion

Through the analysis of the economy and reliability of centralised and distributed energy storage, the suitable hybrid microgrid system type can be obtained, and the specific conclusions are as follows:

(1) Centralised energy storage is applicable to the hybrid microgrid system with small scale, small DC system and low reliability.
(2) Distributed energy storage is applicable to the hybrid microgrid system with large scale, large DC system and high reliability.
(3) In the certain range of average failure rate, the net gain decreases with the increase of average failure rate.

7 References

[1] Jianhua B., Songxu X., Jun L., et al.: ‘Roadmap of realizing the high penetration renewable energy in China’, Proc. CSEE, 2015, 35, (14), pp. 3699–3705
[2] Peng L., Weina X., Zeyuan Z., et al.: ‘Optimal operation of microgrid based on improved gravitational search algorithm’, Proc. CSEE, 2014, 34, (19), pp. 3073–3079
[3] Singh P., Kothari D.P., Singh M.: ‘Integration of distributed energy resources’, Res. J. Appl. Sci. Eng. Technol., 2014, 7, (1), pp. 91–96
[4] Xiangjun W., Bo Z., Hongbin W., et al.: ‘Optimal sizing analysis of grid-connected hybrid AC–DC microgrid’, Autom. Electr. Power Syst., 2016, 40, (13), pp. 55–62
[5] Suhua L., Lin Y., Yaowu W., et al.: ‘Optimizing deployment of battery energy storage based on lifetime prediction’, Trans. China Electrotech. Soc., 2015, 30, (4), pp. 265–271
[6] Kerdphol T., Fuji K., Mitani Y., et al.: ‘Optimization of a battery energy storage system using particle swarm optimization for stand-alone microgrids’, Int. J. Electr. Power Energy Syst., 2016, 81, pp. 32–39
[7] Kerdphol T., Qudaih Y., Mitani Y.: ‘Optimum battery energy storage system using PSO considering dynamic demand response for microgrids’, Int. J. Electr. Power Energy Syst., 2016, 83, pp. 58–66
[8] Xiao J., Liang H.S., Yu T.C., et al.: ‘A capacity optimization method for hybrid energy storage system considering SOC and efficiency’, IET Renewable Power Generation Conf., 2013, p. 2.23
[9] Yue M., Wang X.: ‘Grid inertial response-based probabilistic determination of energy storage system capacity under high solar penetration’, IEEE Trans. Sustain. Energy, 2015, 6, (3), pp. 1039–1049
[10] Abuelrub A., Singh C.: ‘Long term energy storage capacity optimization in energy buffer system’. 2014 IEEE PES General Meeting Conf. Exposition, 2014, pp. 1–5
[11] Qiong T., Bingyu S., Gang Y., et al.: ‘Optimal allocation method of distributed energy storage system in high photovoltaic permeability distribution network’, High Voltage Technol., 2016, 42, (7), pp. 2158–2165
[12] Xiao J., Zhang Z., Bai L., et al.: ‘Determination of the optimal installation site and capacity of battery energy storage system in distribution network integrated with distributed generation’, IET Gener. Transm. Distrib., 2006, 10, (3), pp. 601–607
[13] Xiaogang W., Zongqi L., Liting T., et al.: ‘Energy storage device locating and sizing for distribution network based on improved multi-objective particle optimizer’, Power Syst. Technol., 2014, 38, (12), pp. 3405–3411
[14] Yang L., Fan C., Tai N., et al.: ‘Energy storage station locating and sizing based on relay protection and improved algorithm’, Trans. China Electrotech. Soc., 2015, 30, (3), pp. 53–60
[15] Jun E.: ‘Energy storage for the electricity grid: benefits and market potential assessment guide’ (Sandia National Laboratories, California and Garth Corey, 2010)
[16] Gangui Y., Xiaodong F., Junhui L., et al.: ‘Optimization of energy storage capacity for relaxing peak load regulation bottlenecks’, Proc. CSEE, 2012, 32, (25), pp. 27–35
[17] Huishi L., Lin C., Sige L.: ‘Monte Carlo simulation based reliability evaluation of distribution system containing microgrids’, Power Syst. Technol., 2011, 35, (10), pp. 76–81
[18] Papathanassiou S., Hatziregion  N., Kai S.: ‘A benchmark low voltage microgrid network’. The CIGRE Symp. Power Systems with Dispersed Generation, Athens, Greece, 2005
[19] Yu J., Min H., An M., et al.: ‘Multi-objective energy management of isolated microgrid’, High Voltage Eng., 2014, 40, (11), pp. 3519–3527
[20] Ming D., Bo W., Bo Z., et al.: ‘Configuration optimization of capacity of standalone PV-wind-diesel-battery hybrid microgrid’, Power Syst. Technol., 2013, 37, (3), pp. 575–581

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