An energy storage capacity optimization method based on partition

Li Yan¹, Zhu Haifeng¹, Tian Fangyuan¹, Deng Kai²*, Li Wen², Tang Xiaobo²

¹ State Grid Jiangsu Electric Power Co., Ltd. Economic Technical Research Institute, Nanjing 210000, China
² School of Electrical Engineering and Automation, Nanjing Normal University, Nanjing, Jiangsu, 210023, China
*Corresponding author’s e-mail: dengkainjnu@163.com

Abstract. With the vision of large-scale deployment of grid-connected distributed energy storage system (ESS) in the distribution network, it is necessary to study the capacity optimization of ESS for striking a balance among investment, renewable energy (RE) consumption, power supply security and price arbitrage. In this paper, an ESS partition model based on the improved flame propagation model is proposed. The results of ESS partition are obtained by constructing indexes such as the flammability of nodes, the wind direction of flame propagation, and the speed of flame propagation. Then, an optimization method for ESS capacity in partition is established, which is to maximize the annual net profit and the integer programming method is used to solve the model. Finally, the effectiveness and feasibility of the method are verified by conducting case studies on the IEEE 33 bus distribution network system. The case study results show that the rational configuration of ESS capacity can improve the economy of planning, and the proposed method can improve the Photovoltaic (PV) local consumption ability and power supply reliability of distribution network.

1. Introduction
In recent years, a large number of distributed generation (DG) is connected to the distribution network. With the development of society, users have increasingly high requirements on the reliability of power supply, and the economic losses caused by line or transformer faults in the distribution network are increasing. The ESS has a good application prospect in consuming RE and guaranteeing load power supply [1]. However, due to the relatively high cost of energy storage investment [2], the economic benefit is not obvious. Therefore, it is necessary to study the distributed energy storage capacity optimization and explore the economic benefits of large-scale distributed ESS development.

At present, a large number of scholars have done research on optimizing the energy storage capacity. Generally speaking, distributed energy storage application scenarios mainly include power supply side [3], power grid side [4] and user side [5]. Existing researches generally establish the distributed energy storage capacity optimization model based on the optimal objective function of total cost or economic benefit. In [6], a method is proposed to evaluate the PV access value of energy storage support, taking the optimal total cost as the objective function. [3,7] analyzed the economic value of distributed energy storage in distribution network in such aspects as auxiliary service, peak load reduction, and reduction of carbon emission, which establishes capacity optimization model considering multiple values with the objective function of maximum annual revenue.
The above literature has carried out a large number of analyses for the economic benefit evaluation of large-scale distributed ESSs connected to the power grid side and the user side. However, there is a certain contradiction between the service scope and economic benefits in practice. There is little literature to study how to weigh the contradiction between service scope and economic benefits. In addition, most of the existing researches are based on intelligent algorithms for model solving, but the calculation process is complicated, and the engineering practicality is limited.

Above all, this paper establishes an energy storage capacity optimization method based on partition. The idea of partition has been a research hotspot in power system. Considering the characteristics of distribution network nodes, topological structure and energy storage power limitation, a distributed ESS service scope division is proposed. The ESS partition results are obtained by constructing indexes such as the flammability of the nodes, the direction of flame propagation and the speed of flame propagation. Based on the ESS partition, a practical solution method for energy storage power is presented. Under the premise of known energy storage power, the optimization model of energy storage capacity is established by taking the objective function of maximum annual net income into consideration of electricity quantity benefit, reliability benefit and electricity price benefit. The feasibility and effectiveness of the proposed partition method and capacity optimization model are verified by using IEEE 33 bus distribution network system.

2. ESS capacity Optimization model

2.1 Objection Function

This paper determines the capacity of the ESS with the goal of maximizing the annual net benefits at the planning level which comprehensively considers the benefits and costs of ESS. In engineering practice, the power and capacity of ESS are usually integer, so the integer programming method is used to obtain the optimal power and capacity of ESS, and its objective function can be expressed as:

\[ f(P_{ESS}, E_{ESS}) = f_1 + f_2 + f_3 - f_4 \]  

In the formula, \( P_{ESS} \) is the optimized power, and \( E_{ESS} \) is the optimized capacity, while \( f_1, f_2, f_3, f_4 \) represent the annual electricity benefit brought of consuming RE, the annual reliability benefit of improving power supply reliability, the electricity benefit using time-of-use (TOU) electricity price and the annual equivalent cost of ESS respectively.

2.2 Benefits Analysis of ESS

2.2.1 Annual Electricity Quantity Benefit

Annual electricity benefit refers to the benefit of reducing wasted solar-power generation capacity after the configuration of ESS [8]. Mathematically, this can be described as follows:

\[ f_1 = N_d \beta_{PV} E_{PV} \]  

\[ E_{PV} = \int_{t_a}^{t_b} P_{CS}(t) dt \]  

\[ P_{CS}(t) = \begin{cases} P_{PV}(t) & P_{PV}(t) \leq P_{ESS} \\ P_{PV}(t) & P_{PV}(t) > P_{ESS} \end{cases} \]  

In the formula, \( N_d \) is the total days of a year, \( \beta_{PV} \) is the generation price of PV, and \( E_{PV} \) is the annual amount of PV capacity to be adopted during planning years. \( t_a \) and \( t_b \) are the starting and ending time for PV to exceed the limit, respectively. \( P_{CS}(t) \) is the charging power of ESS consuming PV, and \( P_{PV}(t) \) is the off-limits power of PV. According to the time sequence relationship between PV output and load output, the out-of-limit power of PV in the partition can be solved.

2.2.2 Annual Reliability Benefit

Annual reliability benefit refers to the benefit of improving power supply reliability after the configuration of ESS [9]. Mathematically, this can be described as follows:
\[ f_z = \sum_{n \in N} \sum_{m \in M_n} \overline{L}_m R_n \gamma (1 - \frac{T_i}{24}) \]  

(5)

In the formula, \( M_n \) is the total amount of nodes with type \( n \) load, while \( \overline{L}_m \) is the average load at bus \( m \) during the power failure. \( \gamma \) is the average annual failure rate of each fault type, and \( R_n \) is the economic loss caused by the failure of the type \( n \) load, \( T_i \) is the service time of ESS.

2.2.3 Annual Electricity Price Benefit

When the configured ESS capacity is larger than the off-limit PV capacity, the excess capacity will generate electricity price benefit. The price benefit refers to the arbitrage of using TOU price, based on this, the ESS can be charged when the price is low and will stop charging when the price is high. Mathematically, this can be described as follows:

\[ f_i = N_i (e_p - e_v)(E_{ess} - E_{pv}) \]  

(6)

In the formula, \( e_p \) and \( e_v \) are peak price and valley price, respectively.

2.3 Annual Cost

The costs of ESS include equipment investment in the initial stage and operation and maintenance cost in the later stage. Annual equivalent cost is related to equipment investment, operation and maintenance cost, lifetime and capital discount rate \([10]\). Mathematically, this can be described as follows:

\[ f_i = (\lambda_P P_{ess} + \lambda_E E_{ess}) \frac{r(1+r)^{y_{ess}}}{(1+r)^y_{ess} - 1} + \lambda_{o&m} P_{ess} \]  

(7)

In the formula, \( \lambda_P \), \( \lambda_E \), \( \lambda_{o&m} \) represent the cost of unit power of ESS( \( ¥/kW \)), the cost of unit capacity of ESS( \( ¥/kW\cdot h \)) and the annual operating and maintenance costs of unit power of ESS respectively. \( r \) is the capital discount rate, and \( y_{ess} \) is the life span of ESS.

2.4 Constraints

In order to ensure the safe and stable operation of the ESS and the buses, the power flow constraints of the system and the constraints of ESS should be considered.

Power flow constraints:

\[ \begin{align*} 
  P_{PV}(t) + P_{grid}(t) &= P_{load}(t) + P_{loss}(t) + P_{ESS}(t) \\
  U_{\min} &\leq U_i(t) \leq U_{\max} 
\end{align*} \]  

(8)

ESS constraints:

\[ \begin{align*} 
  0 &\leq P_{ess,c}(t) \leq P_{ess} \\
  0 &\leq P_{ess,d}(t) \leq P_{ess} \\
  E_{ess,c} &= \int_{t_1}^{t_2} P_{ess,c}(t)dt \leq E_{ess} \\
  E_{ess,d} &= \int_{t_1}^{t_2} P_{ess,d}(t)dt \leq E_{ess} \\
  0.1 &\leq SOC \leq 0.9 
\end{align*} \]  

(9)

In the formula, \( P_{PV}(t) \), \( P_{grid}(t) \), \( P_{load}(t) \) and \( P_{loss}(t) \) are the output power of PV system, the output power of power grid, the power of load and the power of loss, respectively. \( U_i(t) \) is the voltage of bus \( I \), while \( U_{\max} \) is the upper limit of \( U_i \), and \( U_{\min} \) is the lower limit of \( U_i \). \( P_{ess,c}(t) \) and \( P_{ess,d}(t) \) are the charge and discharge power of ESS, respectively. \( E_{ess,c} \) and \( E_{ess,d} \) are the charge and discharge capacity of ESS, respectively. \( t_{c1} \) and \( t_{c2} \) correspond to the start and end time of charging, respectively. \( t_{d1} \) and \( t_{d2} \) correspond to the start and end time of discharging, respectively. SOC is the state of charge of ESS.
3. Improved flame propagation model

3.1 Flame Propagation Model
In fact, once the flame is ignited, it will spread around in the combustible medium. Assuming that the combustible medium around is uniform, the flame will spread uniformly around until it encounters non-combustible substance (boundary) or adjacent flame. After the combustible medium is exhausted, the flame goes out, and the ashes produced by flame combustion is the range of flame propagation.

Assuming a set of central points $\Omega={\Omega_1, \Omega_2, \ldots, \Omega_n}$, $3 \leq n \leq N$, then the flame propagation region of arbitrary points can be represented as follows:

$$V(\Omega_i) = \bigcap_{x \in \Omega_i} \left\{ x \mid d(x, \Omega_i) \leq d(x, \Omega_j) \right\} \quad (i = 1, 2, \ldots, n)$$  \hspace{1cm} (10)

In the formula, $V(\Omega_i)$ is the spread range of flame center for $\Omega_i$, while $d(x, \Omega_i)$ is the euclidean distance between the point $x$ and flame center $\Omega_i$, and $x$ is the point on the plane.

The division of ESS service area can draw on the flame propagation model, with the ESS access point as the center of the flame, spreading in all directions along the road. The ashes generated by flame combustion are the ESS service area.

3.2 The Flammability Index of Bus
This paper mainly considers the role of ESS connected to the distribution network in consuming PV output power and improving the reliability of power supply. Therefore, PV and important load buses should be prioritized in the ESS service area. The flammability index of nodes $s_i$ is defined as the product of node power and the membership degree $\lambda_n$ to quantitatively evaluate the priority of the bus in the ESS service area. Mathematically, this can be described as follows:

$$s_i = \sum_{n=1}^{N} \lambda_n P_{in}$$

$$\lambda_n = \frac{\Delta g_i - \Delta c}{\Delta c}$$  \hspace{1cm} (11)

In the formula, $\Delta c$ is the unit investment of ESS, $\Delta g_i$ is the unit benefit generated by type $n$ power node, and $P_{in}$ is the power of type $n$ in node $i$.

When $s_i$ exceeds 5%, it has economic benefit to divide node $i$ into the ESS supply area. Otherwise, it has no benefit. In order to maximize the economic benefits of ESS, the threshold value $s_0$ of $s_i$ can be set. When $s_i$ is lower than $s_0$, it is generally considered that the node is not combustible. When $s_i$ is higher than $s_0$, the node is considered combustible, and these nodes are taken as alternative nodes of energy storage partition.

3.3 The Direction of Flame
The division of ESS service area should not only ensure the load power supply and consuming PV energy as much as possible, but also facilitate the operation and management of the distribution network. Therefore, in the process of flame propagation, factors such as the location and topological structure of the bus in the distribution network are taken into consideration. The concepts of downwind and upwind of flame propagation are introduced to describe the network topology. Downwind means that ESS and load nodes are on the same branch or line along the current trend direction. The upwind means the opposite direction of the power flow, or ESS and load nodes are in different branches or lines. Therefore, the wind direction $f_i$ is introduced to comprehensively evaluate the priority of the bus. Mathematically, this can be described as follows:

$$f_i = (\delta_1 s_i + \delta_2 p_i) c_i$$  \hspace{1cm} (12)

In the formula, $\delta_1$ and $\delta_2$ are weighting factors, $p_i$ is the topological coefficient=$m_i/n_i$, while $m_i$ is the branch number of the bus $i$, $n_i$ is the layer number of the bus $i$, and $c_i$ is coefficient of node tidal direction. When node $i$ is in the downstream direction of the flame, $c_i$ equals 1. Otherwise, $c_i$ equals 0.5.
IEEE 13 bus distribution network is taken as an example to illustrate the practical significance of the above parameters. As shown in figure 1, it is assumed that the access point of ESS is node 3, and the access points of PV system are node 5 and 12. Compared with node 4, node 2 has more branches than node 4, and node 2 has fewer layers than node 4, so \( p_2 > p_4 \). Node 2 is in the upwind position, and node 4 is in the downwind position, so \( c_2 = 0.5, c_4 = 1 \). On the premise that the flammability indexes of node 2 and node 4 are known, the wind direction of the two nodes can be judged and the priority of the two nodes can be finally determined.

![Figure 1. IEEE 13 bus distribution network structure](image)

**Figure 1. IEEE 13 bus distribution network structure**

### 3.4 The Propagation Speed of Flame

The propagation speed of flame is constant in the conventional flame propagation model. In fact, as the service radius of ESS increases, the load rate of ESS increases, then propagation speed will decrease. According to the current load rate of ESS and power supply radius, the flame propagation speed \( v_i \) is constructed. Mathematically, this can be expressed as follows:

\[
  v_i = \alpha_1 (1 - l_i) + \alpha_2 r_i
\]

\[
  l_i = \frac{\sum_{j \in \Omega} P_U + P_i}{P_U}
\]

\[
  r_i = \frac{D_i - D_0}{D_i}
\]

In the formula, \( l_i \) is the load rate of ESS after the bus \( i \) belongs to the service area, while \( r_i \) is the service radius of ESS, \( \alpha_1 \) and \( \alpha_2 \) are weighting factors. \( P_U, P_i \) are the upper limit power of ESS in partition, the power of bus \( i \), respectively, and \( P_j \) is the total power of the buses which belong to the service area. \( D_0 \) is the reference value of the service radius, and \( D_i \) is the actual distance from bus \( i \) to the access point of ESS.

### 4. Capacity optimization process of ESS based on partition

#### 4.1 Capacity Optimization Process

![Figure 3. Capacity optimization process](image)
This paper mainly includes ESS partition algorithm and capacity optimization model. The specific process for capacity optimization based on ESS partition are as follows:

4.2 Adjustment of Flame Diffusion Direction
During the flame diffusion process, if the service radius in a certain direction exceeds the reference value, the diffusion in this direction ends. The flame needs to adjust its direction of diffusion until the end of the diffusion in all directions.

In addition, the adjacent flames will meet during flame diffusion. As shown in figure 3, the dashed arrows indicate the direction of flame diffusion. In this case, it is only necessary to determine the attribution problem of the boundary node when we are adjusting the diffusion direction of the two flames.

Two ESS access points are used as flame cores respectively. The boundary node belongs to the ESS service area with large product by calculating \((f_{iV_i})_1\) and \((f_{iV_i})_2\).

4.3 ESS Power and Capacity Determination
According to the flammability index of nodes, all the alternative nodes have economic value and high return on investment. Therefore, the ESS power in the partition is the sum of the power of alternative nodes in the partition, which can be expressed as follows:

\[
P_{\text{ESS},n} = \max\left\{ \sum_{i \in \Omega} P_i(t), \sum_{i \in \Omega} P_i(t) \right\}
\]  

(16)

In the formula, \(P_{\text{ESS},n}\) is the configured power of ESS in partition \(n\).

5. Case study

5.1 The data of examples
IEEE 33 bus distribution network is used as an example, and the distance between nodes is set to 0.2km. The total load is 3715kW+j2300kvar. The load power of each node is shown in [11]. For the convenience of analysis, the industrial load is defined as the power over 400kW, the commercial load is defined as the power between 100kW and 400kW, and the residential load is defined as the power below 100kW. 200kW PV systems access at node 12, 14, 17, 21, 25, 26 and 32, 500kW PV system accesses at node 24. The total PV capacity of is 1900kW. When the PV system is not equipped with energy storage, the power is only consumed locally. When the PV output is high, the phenomenon of light abandoning will occur. It is assumed that the ESS access points are known, and nodes 2, 17, and 32 are taken as access points. The system’s rated voltage is 12.66kV, the single ESS access power lower limit \(P_D\) is 400kW, and the power upper limit \(P_U\) is 6000kW [12]. The load peak price period is from 18:00 to 22:00, and the valley price period is from 22:00 to 8:00.

Since the load curve corresponding to different types of loads has different trends, this paper considers the load and the timing of PV output. The curves of residential load, industrial load, commercial load, and PV output are all using the typical daily curves provided by Homer software developed by the National Renewable Energy Laboratory (NREL).

Table 1 shows the loss due to power out of various load [13]. Table 2 gives the system parameters required for the example [14].

| Table 1. Outage Cost Functions of All Kinds of Customer(¥/kW). |
|-----------------|---|---|---|---|
| Duration        | 20min | 1h | 4h | 8h |
| residential load| 0.465 | 2.4 | 24.57 | 78.45 |
| commercial load | 14.85 | 42.76 | 156.86 | 415.04 |
| industrial load | 19.34 | 45.43 | 125.82 | 279.04 |
### Table 2. System Parameters

| Parameters  | Values | Parameters  | Values |
|-------------|--------|-------------|--------|
| r           | 0.05   | S_0         | 5      |
| β_PV(¥/kW) | 1.12   | Y_ESS(a)    | 10     |
| λ_P(¥/kW)  | 1000   | T_γ(h)      | 5      |
| λ_E(¥/kW*h)| 1880   | γ(f/a)      | 0.34   |
| λ_O&M(¥/kW)| 24     | c_p/c_e(¥/kW*h)| 0.88/0.28 |
| D_0(km)    | 1.2    | N_δ(days)   | 365    |

### 5.2 The result of energy storage partition

Results of ESS partition are obtained based on improved flame propagation model. As shown in figure 4, the triangles in the figure represent alternative nodes.

According to the partition result, the load power of alternative nodes in each partition and the PV output power limit are obtained. According to equation (16), the energy storage power in the partition can be calculated. The specific data is shown in table 3.

#### Table 3. Node Power and ESS Power of Each Partition.

| Partition | Load Power/kW | Limited Power/kW | ESS Power/kW |
|-----------|---------------|------------------|--------------|
| 1         | 1460          | 490              | 1460         |
| 2         | 680           | 140              | 680          |
| 3         | 120           | 405              | 405          |

#### Table 4. Comparison of the data of ϕ_i and losses before and after the partition

| Index | Partition  | ϕ_i | Losses (10^3¥)/a |
|-------|------------|-----|-----------------|
|       | 1          | 0.53|                 |
|       | 2          | 0.27|                 |
|       | 3          | 0.29|                 |
| Before| 0.53       | 0.27| 0.29            | 172.6 |
| After | 1.00       | 1.00| 0.67            | 49.2  |

### 5.3 Result of energy storage capacity optimization

Based on the above partitioning results which is got by the ESS capacity optimization model presented in this paper, the integer programming method is used to solve the ESS capacity in each partition. Since each partition calculation method is similar, the partition 1 is taken as an example. The depth of discharge(DOD) of ESS is set to 80%, and the relationship between net profit and capacity is shown in figure 5.

It can be seen from figure 5 that when the power is constant, as the capacity increases, the net income increases slowly and then increases rapidly. As the capacity continues to increase, the net income will decrease, and there will also be a process of slowly decreasing first and then decreasing rapidly. This is because at the beginning stage, the profits are mainly due to the electricity quantity benefits and part of the reliability benefits. When capacity continues to increase to exceed the optimal value of ESS capacity,
the configured capacity is larger than the excess PV output capacity, so the electricity quantity benefits reach the maximum value. Meanwhile, the maximum discharge capacity in the peak price period is certain because of the constant ESS power. When the capacity continues to increase beyond this fixed value, the electricity price benefit will also get the maximum value, resulting in the decrease of the net profits. According to the calculation, when the 1460kW/6240 kW•h ESS is configured, the net profits reach a maximum of 637,500¥. Similarly, the relationship between net profits and ESS capacity of partition 2 and partition 3 is shown in figure 6. After calculation, when the partition 2 is equipped with an ESS of 680kW/2980 kW•h, the net profits reach a maximum value of 220,800¥. When Partition 3 is equipped with an ESS of 405kW/2530 kW•h, the net profits reach a maximum of 187,900¥.

The index $\phi_i$ is proposed to illustrate the PV output local consumption ability. The total electrical energy actually consumed during the PV output is divided by the total electrical energy generated during the output phase to assess the local consumption of the PV. Table 4 gives a comparison on the data of PV output local consumption ability and the load outage loss before and after the partition.

It can be seen from table 4 that the PV output local consumption after partitioning is increased. In addition, the loss of power outages also decreased.

6. Conclusions
1. The capacity optimization method based on ESS partition can reduce the active power network loss of the system, improve the local consumption of PV and the power supply reliability of the distribution network. The ESS partition weighs the contradiction between the scope of service and the economic benefits to some extent.
2. Under the condition of current ESS cost, using ESS to consume RE has a good business prospect. In addition, giving full play to the multiple economic values of ESS is the key to the ESS business model in the future.

Acknowledgements
This work was supported by Science and technology project funding of State Grid Jiangsu Electric Power Co., Ltd. (J2019055)

References
[1] Sabihuddin, S., Kiprakis, A.E. (2015) A Numerical and Graphical Review of Energy, Storage Technologies. I. Energies, 8(1):172-216.
[2] Mehrjerdi, H. (2019) Simultaneous Load Leveling and Voltage Profile Improvement in Distribution Networks by Optimal Battery Storage Planning. J. Energy, 181:916-926.
[3] Li, G.D., Li, G.Y., Zhou, M. (2019) Model and application of renewable energy accommodation capacity calculation considering utilization level of inter-provincial tie-line. J. Protection and Control of Modern Power Systems, 4(4):1-12.
[4] Nick, M., Hohmann, M. (2015) Optimal Location and Sizing of Distributed Storage Systems in Active Distribution Networks. In: IEEE Grenoble Conference. France. pp. 232-240.
[5] Xue, J.H., Ye, J.L. (2016) Economic feasibility of user-side battery energy storage based on whole-life-cycle cost model. J. Power System Technology, 40(8):2471-2476.
[6] Yan, Z.M., Wang C.M. (2012) Capacity Plan of Battery Energy Storage System in User Side Considering Power Outage Cost. J. Automation of Electric Power Systems, 36(11):50-54.
[7] Fei, T., Marko, A. (2017) Business case for distributed energy storage. In: International Conference & Exhibition on Electricity Distribution. Glasgow. pp. 1605-1608.
[8] Seyed, A.A. (2013) Optimum Microgrid Design for Enhancing Reliability and Supply-Security. J. IEEE Transactions on Smart Grid, 3(3):1567-1575.
[9] Herder, P.M., Ajah, A.N. (2015) Integration of societal outage cost into infrastructure design and maintenance optimization. In: Proceedings of the IEEE International Conference on Systems, Man and Cybernetics. San Antonio, pp. 265-271.
[10] Mehrjerdi, H., Hemmati, R. (2019) Electric vehicle charging station with multilevel charging infrastructure and hybrid solar-battery-diesel generation incorporating comfort of drivers. J. Journal of Energy Storage, 26:1-9.

[11] Liu, H., Wang, W., Tang, F. (2019) Optimal operation strategy for dispersed wind farms based on variable power factor. J. Journal of Solar Energy, 40(2):387-395.

[12] China Electric Power Corporation Standard. (2018) Design code for distributed energy storage connecting to distribution network. China Electric Power Publishing, Beijing.

[13] Gao, F., Yang, K. (2013) Cycle-life energy analysis of LiFePO_4 batteries for energy storage. J. Proceeding of the CSEE, 33(5):41-45.

[14] Wu, M., Ren, X.J. (2018) Optimal Allocation Method for Capacity of Power Supply System in Industrial Park Under New Electricity Market Reform. J. Automation of Electric Power Systems, 42(5):2-8.