Influence of Distributed Residential Energy Storage on Voltage in Rural Distribution Network and Capacity Configuration

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Abstract. Large-scale access of distributed residential photovoltaic (PV) in rural areas has solved the voltage problem to a certain extent. However, due to the intermittency of PV and the particularity of rural residents' power load, the problem of low voltage in the evening peak remains to be resolved. This paper proposes to solve the problem by accessing residential energy storage. Firstly, the influence of access location and capacity of energy storage on voltage distribution in rural distribution network is analyzed. Secondly, the relation between the storage capacity and load capacity is deduced for four typical load and energy storage cases when the voltage deviation meets the demand. Finally, the optimal storage position and capacity are obtained by using PSO and power flow simulation.

1. Introduction

Distribution network as an important infrastructure in rural areas, the stability of power supply system and the reliability of power quality is essential for rural economic development and the improvement of farmers' living standards [1]. Rural power distribution network has long power lines, while the load is dispersed, seasonal, and has a large difference between peak and valley, resulting in low voltage problems at the end of the line [2]. In recent years, high-power electrical equipment such as air conditioners and refrigerators have entered rural households, and the large increase in electricity consumption has caused more pressure on rural distribution networks. In addition to the existing governance measures, with the development of distributed power supply, many scholars have proposed to access the distributed power supply in rural power distribution network to reduce power transmission, then lifting the distribution network voltage. But the distributed power dispersed in distribution network of power has dual influence quality, which has practical significance to deeply analyse its influence on node voltage based on effective consumptive distributed power supply.

The daily load characteristics of rural residents is the "three peaks and three valleys" [3], as shown in Fig.1. The distributed PV is intermittent, even if the PV capacity is large enough, it can only affect the day voltage of the distribution network, and there will still be low voltage at the peak of the power consumption at the end of the line at night. As shown in Fig.2, it can be seen that the peak voltage during daytime is lifted when 1kW and 2kW PV are added to a low voltage node of the transmission line respectively, and the voltage will exceed the upper limit when the PV capacity is too large, but...
low voltage always exists in the late peak. As a kind of distributed power supply, energy storage can compensate for the power fluctuations caused by intermittent PV output, because it can store energy when the power supply has balance and supply power to the load when the power supply is insufficient. Therefore, this paper considers to solve the problem in rural distribution network by adding energy storage devices, and analyzes the optimal access position and capacity of energy storage.

Only the discharge process of stored energy is considered in the analysis, because the main research is the effect of energy storage on the peak voltage in the evening.

2. Influence of energy storage location and capacity on distribution network voltage

Fig. 3 is a simple low voltage transmission line and load distribution. There are $N$ users on the line, each user load is $P + jQ$, the length of the line between the $n$ and the $n+1$ is $L_n$, the corresponding line impedance is $L_n(R + jX)$ and the capacity of the storage battery connected to the $i$ point is $P_i$

\[ \Delta U_{S_j} = \Delta U_{S_{j-1}} + \Delta U_{S_{j,N}} \]  
\[ \Delta U_{S_{j-1}} = \frac{j}{2} (j-1) \frac{PR_i}{U_N} \]  
\[ \Delta U_{S_{j,N}} = j(N-j+1) \frac{PR_i}{U_N} \]

Therefore, the voltage drop of $j$ is:

\[ \Delta U_{S_j} = \frac{j}{2} (2N - j + 1) \frac{PR_i}{220} \]

\[ j \equiv (1, N) \]
In the i point of the distribution network access capacity of \( P_B \) storage battery. Because the equivalent impedance of the load is far greater than the transmission line’s, the influence of energy storage on the voltage is mainly shown in the line before the access point i. By lifting the voltage of the distribution network indirectly affect the voltage after the i point. So set the voltage drop caused by access energy storage is negative, voltage drop of j node when there is only energy storage is:

\[
\Delta U_{sj} = \begin{cases} 
-\frac{P_i R_i}{220}, & j \in [i, i] \\
-\frac{P_i R_i}{220}, & j \in [i+1, N] 
\end{cases}
\]  

(3)

So, the voltage drop of j at any point is \( \Delta U_j = \Delta U_{sj} + \Delta U_{Bj} \), and the voltage at j is \( U_j = 220 - \Delta U_j \). It can be seen that the position and capacity of the energy storage will affect the voltage distribution.

If \( A = \frac{P_i R_i}{220}, B = \frac{P_i R_i}{220} \) is set, the voltage of j point is:

\[
U_j = \begin{cases} 
220 - \frac{1}{2}(2N - j + 1)A + jB, & j \in [i, i] \\
220 - \frac{1}{2}(2N - j + 1)A + jB, & j \in [i+1, N] 
\end{cases}
\]  

(4)

Taking the node j as the variable, the change of node voltage in the position and capacity of each node is analyzed.

(1) When \( j \in [i, i] \), \( \Delta U_j = \frac{j}{2}(2N - j + 1)A - jB \)

The analysis has shown that \( \Delta U_j \) is monotone increasing when \( j \in [i, N + \frac{1}{2} - \frac{B}{A}] \) and \( \Delta U_j \) is monotone reduction when \( j \in [N + \frac{1}{2} - \frac{B}{A}, 2(N + \frac{1}{2} - \frac{B}{A})] \). At the \( j = N + \frac{1}{2} - \frac{B}{A} \) point, \( \Delta U_j \) has the maximum value that is the lowest voltage point.

① If \( i < N + \frac{1}{2} - \frac{B}{A} \) and \( \Delta U_j \) increase monotonically, the voltage before i tends to decrease gradually.

② If \( i > N + \frac{1}{2} - \frac{B}{A} \), according to the different energy storage capacity, the voltage distribution is different:

a. If \( N + \frac{1}{2} - \frac{B}{A} > 0 \), that is \( B < A(N + \frac{1}{2}) \), the voltage before the i node firstly decrease and then increased, and the lowest voltage is at \( j = N + \frac{1}{2} - \frac{B}{A} \);

b. If \( N + \frac{1}{2} - \frac{B}{A} < 0 \), that is \( B > A(N + \frac{1}{2}) \), at this time \( \Delta U_j < 0 \) and only a monotonically decreasing part, so the voltage before the i node is gradually rising.

(2) When \( j \in [i+1, N] \), \( \Delta U_j = \frac{j}{2}(2N - j + 1)A - jB \)

Here the \( \Delta U_j \) increases monotonically and the voltage decreases gradually after the i point.

It can be seen that the voltage of each node rises in different degrees after the energy storage is used in the distribution network and the voltage rise of the point that access the energy storage is the most obvious. The position of accessed is near the end of the wire transmission, the overall voltage rise more obvious. With the increase of the energy storage capacity, the voltage rise is more obvious, but excessive capacity leads to power reverse flow, then resulting in voltage exceeding the upper limit.

3. Analysis of typical scenes

For different load distribution, the best access position of energy storage may be different. If the whole transmission line load total power is \( P_L \), transmission line length of \( L \), set up four kinds of typical
load distribution as follows: the average distribution, increasing distribution, decreasing distribution and end spurt distribution are analyzed [5], as shown in Fig. 4.

The access mode of energy storage is given same as Fig. 4, and the total power of energy storage is $P_B$, the voltage loss of the transmission line can be expressed:

$$P(x) = P_L + P_B$$

Therefore, in order to make the whole distribution network do not appear the upper limit of the voltage, load and energy storage

$$B \leq P \leq L$$

When: $\Delta U_L$ and $\Delta U_B$ are voltage drop caused by load and storage access, $r$ is the unit length of equivalent resistance of transmission line, $l$ is the distance that access point from the head end of the transmission line. Through the integration of four distribution functions of Figure 4, the corresponding voltage formula is obtained (the foot marker represents the load L or the energy storage B):

1. **Average distribution**:

$$\Delta U_x = \frac{P_x \cdot rL}{220} \left(1 - \frac{l}{2L}\right)$$

2. **Increasing distribution**:

$$\Delta U_x = \frac{rl}{220} \left(P_x \frac{1}{2} P_{x2} + \frac{P_x - P_{x2} \cdot L^2}{3L^2}\right)$$

3. **Decreasing distribution**:

$$\Delta U_x = \frac{rl}{220} \left(P_x \frac{l^2}{3L^2} + \frac{P_{x3} \cdot l}{3L} + \frac{P_x + P_{x3} \cdot l}{2}\right)$$

4. **End spurt distribution**:

$$\Delta U_x = \frac{rl}{220} \left(P_x \frac{1}{2} P_{x4} \cdot l\right)$$

### Table 1 Relationship between load capacity and energy storage capacity under different load and load distribution conditions

| Load distribution | Average distribution | Increasing distribution | Decreasing distribution | End spurt distribution |
|-------------------|----------------------|-------------------------|------------------------|-----------------------|
| Average           | $P_L < P_x$          | $P_L < P_x + \frac{L}{2} P_{x2}$ | $P_L < P_x + \frac{L}{3} P_{x3}$ | $P_L < P_x + \frac{L}{4} P_{x4}$ |
| Increasing        | $P_L < \frac{P_x}{3} + \frac{L}{2} P_{x3}$ | $P_L < P_x + \frac{L}{3} (P_{x3} + P_{x4})$ | $P_L < P_x + \frac{L}{4} (P_{x3} + P_{x4})$ | $P_L < P_x + \frac{L}{5} (P_{x3} + P_{x4})$ |
| Decreasing        | $P_L < P_x + \frac{L}{3} P_{x3}$ | $P_L < P_x + \frac{L}{4} (P_{x3} + P_{x4})$ | $P_L < P_x + \frac{L}{5} (P_{x3} + P_{x4})$ | $P_L < P_x + \frac{L}{6} (P_{x3} + P_{x4})$ |
| End spurt         | $P_L < 2P_{x3} - L \cdot P_{x4}$ | $P_L < 2P_{x3} - L \cdot (3P_{x3} + P_{x4})$ | $P_L < 3P_{x3} - L \cdot (3P_{x3} + P_{x4})$ | $P_L < 4P_{x3} - L \cdot (3P_{x3} + P_{x4})$ |

In the "power quality, power supply voltage operation deviation" of GB/T 12325-2008 , requires "220V single-phase supply voltage deviation is nominal voltage of -10%~+7%". Assuming that the first terminal voltage of the distribution network is within the allowable voltage deviation range, the condition that no voltage exceeds the limit at any point is $\Delta U_L \cdot \Delta U_B > 0$. Therefore, in order to make the whole distribution network do not appear the upper limit of the voltage, load and energy storage
under different distribution conditions, the capacity of both should meet the relationship of Table 1. We can see that when $P_{L2} = P_{L3} = P_{L4}, P_{B2} = P_{B3} = P_{B4}$, no matter what is the load distribution, the minimum capacity is required for the terminal access mode of energy storage. For the same kind of storage access mode, the capacity needed of decline distribution is less than other distribution modes.

4. Analysis of examples
The system of Fig. 3 as example, the voltage of line is 220 V, type of line is LGJ - 25 mm$^2$ and the impedance of the unit length is $1.326 + 0.352 \, \Omega/km$. There are 10 users on the line, total consumption of active power is 30kW and reactive power is 0kW, the distance between adjacent users was 30m.

4.1. The change of voltage after the energy storage is connected when the load is average distributed At this point, the load of each user node is 3 kW, and the voltage of each node calculated by the power flow calculation is shown in Fig.5. It can be seen that the voltage is lower than the lower limit from the fifth node, which resulting in insufficient supply voltage for end users, and affects the normal use of household appliances.

Fig. 5 The voltage distribution of the primary transmission line when the average load distribution

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Fig. 5

The voltage distribution of the primary transmission line when the average load distribution

a. Energy storage of different capacity access to 5 node

b. Energy storage of 10kW access to different nodes

Fig. 6 The distribution of the line voltage under the different energy storage capacity and position

Fig. 6 is the distribution of the voltage of the transmission line when the energy storage capacity and the access position are different. Through analysis, we can draw the following conclusions:

1. With the increase of the storage capacity of the line, each user node voltage is uplift. For access to different storage capacity, there are three trends in voltage distribution: gradually reduced, declining-rising-declining, increase first and then decrease.

2. When the same capacity of the energy storage access to the different locations of the line, the voltage distribution is different. And the access location is closer to the end of the line, the more obvious the effect of the voltage rise of the transmission line.

The simulation results show that the influence of the capacity and position of the energy storage on voltage distribution is the same as that the second section. It shows that it is feasible to use the model of distribution network to simulate and analyze the corresponding voltage characteristics.
4.2. Optimal location and capacity of energy storage based PSO

The energy storage capacity optimization is usually carried out from the different angles of voltage quality, power grid loss and economic benefits, so as to ensure the safety, stability and economic operation of the distribution network. Under the research background of rural distribution network, the economy is one of the main factors to consider, so the goal of this configuration is to minimize the total energy storage capacity on the basis of the voltage meets the requirements.

It is difficult to solve the optimal allocation of energy storage by traditional algorithms. A lot of literature by comparing several optimization algorithms have found that particle swarm optimization (PSO) is more suitable for solving the optimal allocation model of energy storage\[6\][7].

(1) Objective function: the total power of discharge of energy storage $P_B$ is minimum

Assuming that the load power is constant in the given time range, that is discharge power of the energy storage is certain. So find the optimal discharge power point, that is to find the optimal allocation of energy storage capacity.

(2) Constraint conditions:
   ① Range of node voltage: $0.9 < U_i < 1.07$
   ② The discharge power is positive: $P_{Bi} \geq 0$

![Fig. 7 The optimal location and capacity of energy storage when load distribution is average](image1)

The optimization results of the average load distribution are shown in Fig.7. The energy storage’s discharge power is 0, indicating that the node does not access energy storage, and the optimized results show that the storage power of 2.03kW and 3.03kW are accessed at 9 and 10 nodes. The voltage distribution before and after the energy storage access is shown in Fig.8.

From the simulation results, it can be concluded that the energy storage capacity of the transmission line can be minimized when the storage energy is connected to the end of the transmission line with the average load distribution. This is the same as the conclusion drawn (2) by using the exhaustion method to simulate the power flow directly.

4.3. The optimal location and capacity of energy storage in different load distribution

a. Load increasing distribution  
b. Load decline distribution  
c. Sudden increase in load end

![Fig. 9 The optimal storage position and discharge power under different load distribution](image2)
When the load distribution of each node is in different distribution state, the optimal position of the energy storage and the discharge power are shown in Fig.9. Fig.10 is the voltage distribution of node before and after the energy storage access.

From the optimization and simulation results, regardless of what is the load distribution based on satisfying voltage requirements, the required capacity is the minimum that is the energy storage cost is the lowest when the storage energy is connected to the end of the transmission line. The results obtained are consistent with the third section.

5. Conclusion

This paper takes the rural distribution network which has access to the household distributed PV as the research background, proposes a method to solve the low voltage problem of the end users at the peak of the night power consumption by accessing the energy storage. Through the theoretical derivation and simulation analysis are as follows:

(1) In the distribution network access energy storage, voltage of each node have different degrees of uplift, where the voltage rise of access point is the most obvious. The closer to the end of the transmission line, the more obvious the voltage rise of the distribution network. With the increase of the energy storage capacity, the voltage rise is more obvious, but excessive capacity leads to power reverse flow, then resulting in voltage exceeding the upper limit.

(2) The position and capacity of the energy storage are different, and the voltage of the transmission line is different. For the nodes before the energy storage access point, the voltage has three trends: gradually reduced, declining-rising-declining, increase first and then decrease. And the node voltage after the access point is gradually decreased.

(3) No matter what kind of distribution the load is, the minimum capacity required for energy storage is the way of terminal access. For the same energy storage access mode, the capacity needed of decline distribution is less than other distribution modes.

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