Study on the Optimal Configuration Strategy of Photovoltaic and Energy Storage in Distribution Network

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Abstract. Aiming at the scenario of joint optimization of distributed optical storage in distribution network, this paper takes the maximum net profit of optical storage system as the goal. At the same time, this paper considers the high cost of energy storage battery, and combines the load characteristics, the energy storage operation characteristics and China's electricity price policy to construct the optical storage system investment income model. On the basis of satisfying the power balance and the performance constraints of the energy storage battery, an optimization model considering the net profit of the optical storage system is established, and the YALMIP toolbox and CPLEX program are used to solve the problem in MATLAB. Finally, the results of the energy storage configuration are tested in the IEEE-33 node system. The test results prove the effectiveness of the optical storage joint optimization configuration strategy based on the net profit of the optical storage system as a technical indicator.

1. Introduction
Solar energy is a renewable energy source. It not only has convenient collection methods, but also does not pollute the resources and environment on the earth. It has great development potential and innate development advantages. The role of Photovoltaic (PV) is to transform solar energy into the electrical energy needed for people's daily lives and work[1–3]. In 2018, China's PV installed capacity has far exceeded other renewable energy sources. However, the safe and stable operation of the distribution network will be affected by the randomness and volatility of solar energy, which will bring a series of problems to the power system[4]. The energy storage device responds quickly, not only can improve the system power quality and reliability, but also cut the peaks and fill the valley, reducing the user's electricity expenses when the peak price of electricity[5,6]. Therefore, energy storage is often connected to the distribution network system[7]. The dilemma of the current energy storage capacity configuration is that the cost of the energy storage battery is high, so the configured energy storage capacity should not be too large.

In view of the two typical loads of residential load and industrial load, considering the high cost of energy storage battery, and in connection with China's electricity price policy and energy storage operation characteristics, this paper constructs an investment model of optical storage system
considering the economics of distribution network users to solve the goal of improving the net profit of the optical storage system. Finally, the optimal solution is simulated in the IEEE-33 node system, and the reasonable analysis is carried out according to the test results. According to the analysis results, reasonable suggestions are given for the energy storage configuration of the users on the distribution network.

2. System characteristic analysis
The typical structure of the distributed optical storage system is shown in Figure 1[8]. The system consists of a photovoltaic cell module system, an energy storage battery system and a local load. The photovoltaic unit and the energy storage unit firstly flow into the DC bus through the DC-DC converter of the system, then enter the DC-AC inverter, and finally supply power to the load through the AC bus.

![Figure 1. Structure of optical storage system](image)

2.1. Typical load characteristics
The typical load curve is shown in Figure 2. This paper focuses on residential and industrial load.

![Figure 2. Typical power load curves](image)

The residential load has seasonal fluctuations and typical characteristics closely related to daily life, and its second peak period often overlaps with the evening peak period of the power system. Industrial users have little fluctuation in power.

2.2. Photovoltaic power generation characteristics
The photovoltaic power generation curve with an installed capacity of 750 kW is shown in Figure 3.

As can be seen from Figure 3, the photovoltaic power generation curve has a distinct single-peak characteristic, and the peak power of the day is probably between 12:00 and 15:00.

3. Optical storage system investment income model

3.1. System cost
Considering the actual situation in China, many users have already installed PV, so the installation cost of PV system will not be considered in the cost. The investment cost of optical storage system $C$ mainly includes the cost of energy storage battery $C_B$, the cost of energy storage bidirectional converter $C_C$ and the cost of energy storage to purchase electricity $C_G$.

$$C = C_B + C_C + C_G$$ (1)
The various cost calculation formulas are as follows:

\[
C_B = E_B I_B \frac{r_0 (1+r_0)^n}{(1+r_0)^n - 1} + u(B)
\]

\[
C_C = P_C I_C \frac{r_0 (1+r_0)^n}{(1+r_0)^n - 1} + u(C)
\]

\[
C_G = \sum_{i=1}^{n} R E_{grid} P_i \frac{(1+g)^y}{(1+r_0)^y}
\]

In Eq. (2), \(E_B\) is the energy storage battery capacity, \(P_c\) is the total power of the energy storage bidirectional converter, \(I_B\) is the unit price of the energy storage battery, \(I_C\) is the unit price of the energy storage bidirectional converter. \(u(B)\) and \(u(C)\) are the two systems later operation and maintenance costs. \(n\) is the system operation period. \(R\) are the similar days. \(E_{grid}\) is the amount of electricity purchased for the storage of energy on the one day of the year. \(p_i\) is the electricity price for the energy storage battery system when it is purchased on the one day of the year. \(g\) is the inflation rate. \(r_0\) is the discount rate.

### 3.2. System revenue

Considering that the country's subsidies for photovoltaics are gradually declining, many regions are promoting non-subsidized work for photovoltaic power generation, so the benefits of photovoltaic power generation subsidies will not be considered in the income. The first part of the system's revenue is that the user does not purchase electricity from the grid, saving electricity through the optical storage system, and thus saving electricity costs \(B_1\). The second part is the income that the photovoltaics sell to the grid after satisfying the load and energy storage demand \(B_2\).

\[
B = B_1 + B_2
\]

The various revenue calculation formulas are as follows:

\[
\begin{align*}
B_1 & = \sum_{i=1}^{n} R (E_{pC} P_i + E_{pE} P_i) \frac{(1+g)^y}{(1+r_0)^y} \\
B_2 & = \sum_{i=1}^{n} R I_{pG} P_{pG} \frac{(1+g)^y}{(1+r_0)^y}
\end{align*}
\]

In Eq. (4), \(E_{pC}\) is the photovoltaic energy absorbed by the load on a typical day of one year. \(E_{pE}\) and \(E_{pG}\) are the electricity discharged from a typical day of one year and the photovoltaic electricity sold to grid. \(p_{pG}\) is the on-grid price of PV of one year.

### 3.3. System net profit

The expression for system net profit \(C_{net}\) is:

\[
C_{net} = B - C
\]

### 4. Optical storage system capacity configuration model

#### 4.1. Objective function
\[
\text{max } f = \text{max } C_{\text{net}} = \text{max}(B - C) \tag{6}
\]

4.2. Constraints

4.2.1 Node power balance constraints. In Eq. (7), \(P_{\text{pv}}\) is the power output of the photovoltaic system. \(P_c\) is the charge and discharge power of the energy storage. When the energy storage discharges, \(P_c\) is a positive value. When the energy storage is charged, \(P_c\) is a negative value.

\[
P_{\text{pv}} + P_c = P_{\text{load}} + P_{\text{grid}} \tag{7}
\]

\(P_{\text{load}}\) is the power consumed by the load. \(P_{\text{grid}}\) is the power transmitted by the optical storage system and the large power grid. When the optical storage system delivers power to the grid, \(P_{\text{grid}}\) is a positive value. When the optical storage system absorbs power from the grid, \(P_{\text{grid}}\) is a negative value.

4.2.2 Energy storage battery performance constraints \([9,10]\). In Eq. (8), \(E_{\text{th}}\) is the energy storage battery capacity. \(P_c\) and \(P_{dc}\) are the energy storage charge and discharge power. \(\varepsilon_c\) and \(\varepsilon_{dc}\) are the binary numbers of whether the energy storage is charged, there must be one in \(\varepsilon_c\) and \(\varepsilon_{dc}\). \(\eta_c\) and \(\eta_{dc}\) are energy storage charge and discharge efficiency. \(S_{\text{SOC}}\) is the state of charge of the energy storage battery. \(E_{\text{rate}}\) is the rated capacity of the energy storage battery. \(D_{\text{OD}}\) is the depth of discharge of the energy storage battery.

\[
\begin{align*}
E_{\text{th}}(t + \Delta t) &= E_{\text{th}}(t) + \varepsilon_c P_c(t) \Delta t \eta_c - \varepsilon_{dc} P_{dc}(t) \Delta t / \eta_{dc} \\
S_{\text{SOC}}(t + \Delta t) &= [E_{\text{th}}(t) + \Delta E_{\text{th}}] / E_{\text{rate}} \\
S_{\text{SOC,min}} \leq S_{\text{SOC}} \leq S_{\text{SOC,max}} \\
D_{\text{OD}} &\leq 0.8 \\
\varepsilon_c + \varepsilon_{dc} &= 1, \varepsilon_c, \varepsilon_{dc} \in \{0,1\}
\end{align*} \tag{8}
\]

4.2.3 Model solving. This paper uses the YALMIP toolbox and the CPLEX program to solve the model.

5. Case analysis

5.1. Basic data

In this paper, a lithium battery is selected as the material of the energy storage battery. The main parameters are shown in Table 1.

| Parameters                        | Values | Parameters                        | Values |
|-----------------------------------|--------|-----------------------------------|--------|
| Energy storage battery price      | 3240   | System operation years/years     | 20     |
| price / (yuan / kWh)              |        | Discount rate                     | 7%     |
| Energy storage battery efficiency | 96%    | Inflation rate                    | 3%     |
| Bidirectional converter price     | 1085   | PV feed-in tariff / (yuan / kWh)  | 0.3780 |
| / (kW)                            |        |                                  |        |
| Bidirectional converter efficiency| 96%    |                                  |        |

This paper selects the power users in Jiangsu Province as the research object, because the electricity consumption and the peak-valley electricity price difference in Jiangsu Province are
relatively large, which provides a large space for the distribution network power users to attain profits from energy storage. In addition, the peak-to-valley electricity price difference in Jiangsu Province is relatively large, providing a large space for the distribution network side power users to arbitrage through the energy storage “low storage and high-level” arbitrage. The electricity price parameters are shown in Table 2.

Table 2. Parameters of electricity price

| Load type       | Peak price / (yuan / kWh) | Flat price / (yuan / kWh) | Valley price / (yuan / kWh) |
|-----------------|---------------------------|---------------------------|----------------------------|
| Residential load| 0.5583                    | —                         | 0.3583                     |
| Industrial load | 1.137                     | 0.722                     | 0.407                      |

In this example, the calculation is performed at 8760 hours per year, and the scheduling interval is 1 h, assuming that the output power of the photovoltaic and load is constant within 1 h. This paper studies the energy storage capacity allocation of residential and industrial loads in the distribution network. The installed capacity of PV installed by residential load and industrial load is 850 kW and 1800 kW respectively. The load data is shown in Table 3.

Table 3. Maximum load of residential and industrial users

| Load type     | Residential load/kW | Industrial load/kW |
|---------------|---------------------|--------------------|
|               | 710                 | 1500               |

5.2. Result analysis

According to the above data, the energy storage capacity of the residential load and the industrial load is configured, and the capacity result and the equivalent load curve are shown in Table 4 and Fig 4.

Table 4. Planning results

| Load type    | $E_b$/ kWh | $P_c$/ kW | Net profit/ ten thousand yuan | Previous net profit/ ten thousand yuan |
|--------------|------------|-----------|------------------------------|---------------------------------------|
| Residential load | 2264.3     | 1400      | 1187.5                       | -1345.2                               |
| Industrial load     | 1385.7     | 971       | -405.14                      | -2976.1                               |

From the results of the configuration, the net profit of both types of load installation energy storage devices has been improved, indicating that the benefits of the planning scheme can be improved by configuring the energy storage based on the calculation parameters. The net profit of industrial users is higher, because the peak price difference between industrial users is larger. From the perspective of the equivalent load curve, the optimized scheduling scheme is implemented and the time-sharing price method is adopted, which effectively reduces the user's purchase of electricity from the grid at the peak hourly price. During this time period, some or all of the power required by the load is provided by photovoltaics and energy storage, which reduces the amount of electricity purchased by the user from the grid. Access to photovoltaic and energy storage systems has reduced the net load of residential and industrial users to a certain extent.
5.3. Impacts on the distribution network
The results of the energy storage configuration were tested in an IEEE-33 node system. In the IEEE-33 node test system, the photovoltaic power generation device and the energy storage device configured in 4.2 are installed on the same node, and according to the load level of the node, in the candidate nodes 2 to 33, the set node 24 is the industrial load. Node 25 is the residential load, and the modified structure is shown in Figure 5.

![Figure 5. Modified IEEE-33 node test system](image)

In MATLAB, the voltage, voltage deviation and network loss of the node in the original distribution network, the original distribution network plus PV, and the original distribution network plus PV plus energy storage are calculated. The node voltage distribution curve is shown in Figure 6.

![Figure 6. Node voltage distribution curve](image)

It can be seen from Figure 6 that the voltage on the branch decreases in the direction of the tidal current flow before the distribution network is connected to the distributed photovoltaic. After the photovoltaic and energy storage are allocated in the distribution network, the original power flow distribution is changed, the node voltage is increased to some extent, and the node voltage does not exceed the limit. The voltage deviation is shown in Table 5.

| Previous load | Previous load +PV | Previous load +PV+ESS |
|---------------|-------------------|------------------------|
| 9.2556*10^-4  | 9.1989*10^-4      | 8.8522*10^-4          |

As can be seen from Table 5, with the addition of photovoltaics, the system voltage deviation will be reduced. After adding energy storage, the system voltage deviation will be further reduced, which indicates that the addition of the energy storage system will suppress voltage fluctuations.

6. Conclusion
This paper considers the load characteristics and electricity price structure of residential users and industrial users to determine the energy storage configuration, selects the distribution network users as the main body of income, and considers the load characteristics, the operational characteristics of energy storage and China's electricity price policy. In the solution process, this paper introduces the YALMIP toolbox and CPLEX program to find the target value to maximize the net profit, thus obtaining a reasonable energy storage configuration.

(1) Through the calculation of two cases of residents and industrial users, configuring energy storage can increase the user's income. Under the condition of peak-to-valley time-of-use electricity price, the net profit of industrial users is much higher than that of residential users, because the peak price difference between industrial users is large.

(2) By configuring the energy storage device, it is possible to prevent users from purchasing electricity during peak hours, and to a certain extent, improve the economic benefits of power users. In
addition, the power supply pressure of the grid at the peak stage has been reduced, which plays an important role in shaving peaks.

(3) The optical storage system network improves the original power flow distribution. After accessing distributed photovoltaics and energy storage, the system operation is more stable, affecting the actual power flow distribution of the system, increasing the voltage of the branch node, reducing the voltage deviation.

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