Two-stage scheduling strategy of air-conditioning load participating in PV absorption of distribution network

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Abstract. Aiming at the grid operation problems brought by large-scale photovoltaic(PV) connection to the distribution network, this paper proposes a two-stage scheduling strategy for air-conditioning load to participate in the PV absorption of distribution network, considering the schedulable capacity of air-conditioning load. First, in the first stage, in the micro-grid layer, each air-conditioning load aggregator(LA) makes a market bidding based on non-cooperative game to determine the day-ahead scheduling plan according to the plan of PV absorption formulated by the micro-grid operator in the past.; In the second stage, in the distribution network layer, when the micro-grid itself cannot fully absorb the PV power and the power is transferred to the main network, resulting in the voltage overlimit problem in the network, the grid company adjusts the voltage by using the schedulable capacity of air-conditioning load. The simulation results show that the strategy proposed in this paper can not only enhance the utilization of PV power and adjust the distribution network voltage, but also improve the profit of the air-conditioning LAs, reduces the regulation cost of the micro-grid operators and the grid company and has high economic efficiency.

1. Introduction
Nowadays, environmental pollution and the shortage of energy resources have become the serious problems faced by the world's development[1]. The wide application of wind, light and other renewable energy is an important way to solve these problems[2]. Among them, due to the advantages of abundant resources and convenient access, PV is widely recognized as the worthiest renewable energy[3]. It is estimated that by 2040, PV power generation will account for the largest proportion of all renewable energy power generation, and most of them will be connected to the medium and low voltage distribution network[4].

Photovoltaic Grid-connection will bring impact on distribution network. The traditional low-voltage distribution network has a single power flow direction, which transfers the power from the main network to the users. Photovoltaic Grid-connection will change the power flow direction of the grid, and the power flow is bidirectional. If the capacity of PV generation is small, the impact on the distribution network can be ignored. However, with the increase of PV permeability, it may cause the capacity overload of point of interconnection of PV and damage the stability of power supply. In addition, due to the randomness and volatility of PV output power, when the PV output is excessive and the distribution network cannot absorb it naturally, it is easy to cause power quality problems such as voltage over-limit in the power grid, which will affect the normal operation of the power grid. Therefore, the PV absorption of low-voltage distribution network should be paid attention to[5].
With the improvement of the power market\cite{6} and the development of demand response technology\cite{7}, more and more people begin to pay attention to regulating the real-time power fluctuation of the system by aggregating the flexible loads such as the air-conditioning on the user side\cite{8}. Literature [9] studies the working characteristics of a single air-conditioning, and then establishes an aggregation model of the residential air-conditioning; Literature [10] establishes a high-precision comprehensive model for a large number of air-conditioning loads to provide a variety of demand response services such as frequency modulation and peak regulation. Literature [11] studies the demand response control strategy of multiple groups of central air-conditioning systems, aiming to reduce the peak demand of buildings, but it only focuses on the regulation effect and ignores the economic benefits; Literature [12] proposes a DRM algorithm to reduce the power demand of the air-conditioning system according to the conditions of room temperature, occupancy level of personnel and current power demand; Literature [13] proposes a voltage control strategy for distribution network based on the coordinated optimization of PV and air-conditioning, but it is not suitable for long-term scale. However, the viewpoints of these studies mainly consider the perspective of system stability and security, and they do not consider the multiple stakeholders in open market environment of power retail side, and in these researches, users or air-conditioning LAs are in a passive position to accept the market price or the scheduling capacity.

Based on the above reasons, this paper proposes a two-stage scheduling strategy considering the participation of air-conditioning load in PV absorption of distribution network to meet the profit of multiple stakeholders. Firstly, the system architecture including micro-grid layer, distribution layer, load layer and main power grid is established. Then, based on the non-cooperative game theory, a PV absorption model of air conditioning load is proposed for the micro-grid layer to meet the profit of users, it determines the day-ahead PV absorption plan with the goal of maximizing the income of the air-conditioning LA; for the distribution network layer, based on the model predictive control, the auxiliary voltage regulation strategy of air-conditioning load participating in the distribution network is proposed to realize dynamic and economic voltage regulation with the goal of minimizing the adjustment cost of power grid companies. Finally, an example is given to verify the effectiveness of the strategy.

2. The system architecture of the strategy

Due to the schedulable capacity of single air-conditioning load is small, but the total amount of them is huge, in order to facilitate the research, in this paper, the air-conditioning load is dispatched in the form of air-conditioning LA, and the system architecture including micro-grid layer, distribution network layer, load layer, control center and main grid is established. There are a certain number of air conditioning loads in the micro-grid layer, and the system structure diagram is shown in Figure 1.

![System structure diagram](image)

Figure 1. System structure diagram

In the first stage, in the micro-grid layer, in order to prevent the capacity overload of point of interconnection of PV, the micro-grid operators determine the capacity and time period for the air-conditioning LAs to participate in PV absorption in the next day, according to the historical load data and PV data. Each air-conditioning LA takes the schedulable capacity of air-conditioning load in their own jurisdiction area as the constraint condition, and with the aim of maximizing its own profits, and makes market bidding together with other aggregators to determine the scheduling plan of each
aggregator in the next day. In the second stage, in the distribution network layer, when the micro-grid itself cannot fully absorb the PV output power, the remaining PV power will be transferred to the distribution network. If the distribution network cannot absorb the remaining PV power naturally, resulting in the problem of voltage over-limit in the network, the grid company will adjust it uniformly, and send the real-time power flow information of the distribution network to the control center. Through the control center, the adjustment amount of the air-conditioning load in each load layer is optimized and allocated with the load information of each air-conditioning LA in the load layer and the goal of minimizing the adjustment cost of the power grid company.

3. Two-stage schedulable strategy of air-conditioning load participating in PV absorption of distribution network

3.1. PV absorption model of air-conditioning load participating in micro-grid

According to the historical load data and PV data, the micro-grid operators determine the time period and capacity for LAs to participate in PV absorption, and announces it to all LAs participating in bidding. It is assumed that the micro network operators determine that there are T periods in which LAs are involved, and the interval of each period is Δt=5 min. In addition, there are n LAs participating in demand response.

3.1.1. The profit function of LAs. When the air-conditioning load participates in the PV absorption of the micro-grid, the micro-grid operator needs to give certain compensation to the aggregator, and the air-conditioning LA also needs to make corresponding compensation to the participating air-conditioning users. Therefore, the total profit of air-conditioning LA $i$ is shown as follows:

$$ u'_i = \sum_{t=1}^{T} (\epsilon'_t - c'_{air,i}) l'_i \Delta t / 60 $$

Where: $\epsilon'_t$ is the compensation price given by the grid company to the LA in period $T$, $\$/kW·h; $c'_{air,i}$ is the compensation price given by the LA $i$ to the air-conditioning user, $\$/kW·h; $l'_i$ is the amount of PV absorption of the LA $i$ in period $T$.

The compensation price given by the micro-grid operator to the LA is determined according to the market price, which is an inverse function with the total amount of PV absorption, which is shown as follows:

$$ \epsilon'_t = a' + b' (Q' - \sum_{i=1}^{n} l'_i) $$

Where, $a'$ and $b'$ are the coefficients of the function of market price respectively; $Q'$ is the PV power that needs to be absorbed at time $t$.

3.1.2. Objective function of air-conditioning LA. When the LA participates in the day-ahead bidding, it will aim at the maximum profit of itself, which is shown as follows:

$$ \begin{align*}
\max (u'_i) &= \sum_{t=1}^{T} ((\epsilon'_t - c'_{air,i}) l'_i \Delta t / 60) \\
\text{s.t.} & \quad 0 \leq l'_i \leq \bar{l}'_i \\
& \quad l' \leq Q'
\end{align*} $$

Where: $\bar{l}'_i$ is the schedulable capacity of LA $i$ in period $t$.  


Since the market price is determined by the total amount of PV absorption, that is to say, the income of LA is not only related to the bidding amount of their own, but also to the bidding amount of other LAs, so the participation of LAs in micro-grid PV absorption bidding is a typical non-cooperative game\cite{14}.

3.2. Distribution Network Voltage Control Based on Air-Conditioning.

As the micro-grid itself may not be able to fully absorb the PV power, in order to reduce the phenomenon of "light abandonment", the remaining PV power will be transferred to the distribution network. If it results in the problem of voltage over-limit, the grid company will send the real-time power flow information of the distribution network to the control center, and require the air conditioning LAs in the load layer to report the schedulable capacity of the air-conditioning load in the area under their jurisdiction, and finally the control center will uniformly optimize the adjustment amount of the air-conditioning load in each load layer.

Because the power flow information of distribution network changes in real time, and the schedulable capacity of air-conditioning load changes with the progress of regulation. If the distribution network state at a certain time is taken as the basis of voltage control, the effect of voltage control will decline rapidly with the advance of time. MPC method is an effective way to solve this problem. In each regulation period, the control center takes the current flow information of the system at the beginning of the current period as the initial state to establish the voltage regulation model within the current period. Based on the schedulable capacity of the air-conditioning load reported by the air-conditioning LA, the adjustment amount of the air-conditioning load in each load layer in the current period can be determined after solving the model. This process is rolled until the adjustment time is satisfied.

3.2.1. Objective function. The adjustment cost of the grid company is the sum of the compensation cost given to the LAs and the total network loss of the system, so the objective function of each optimization period under the MPC method is described as

\[
F = \min[\alpha p_{\text{sum}} + \beta \sum_{j=1}^{N_{\text{LA}}} c_{\text{LA}} p_{\text{air},j} \Delta t / 60]
\]  

(4)

Where, \(F\) is the adjustment cost of the grid company; \(p_{\text{sum}}\) is the system network loss after regulation; \(p_{\text{air},j}\) is the amount of adjustment of LA \(j\); \(c_{\text{LA}}\) is the compensation price given by the grid company to the LA, \$/kW·h; \(\Delta t\) is the duration of each adjustment period; \(\alpha, \beta\) are the normalization coefficient of network loss and compensation cost. This paper focuses on the reduction of compensation cost, so take \(\alpha = 0.2, \beta = 0.8\). If there is a higher requirement for network loss and a lower requirement for total adjustment cost, additional values can be set for \(\alpha, \beta\) according to the requirement.

3.2.2. Constraints. At the same time, the strategy should also meet the constraints of power flow, voltage (per-unit value) and schedulable capacity of air-conditioning load, as follows:

\[
\begin{align*}
P_i &= V_i \sum_{j=1}^{N} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\
Q_i &= V_i \sum_{j=1}^{N} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \\
0.97 \text{p.u.} &\leq V_i \leq 1.03 \text{p.u., } \forall i \in N \\
P_{\text{air},i} &\leq P_{\text{air,max}}
\end{align*}
\]  

(5)  

(6)  

(7)

Where, \(N\) is the total number of distribution network nodes; \(V_i\) and \(V_j\) are voltage amplitude of node \(i\) and node \(j\) respectively; \(G_{ij}\) is the conductance of branch \(ij\); \(B_{ij}\) is the charge of branch \(ij\); \(\theta_{ij}\) is the phase angle of branch \(ij\); \(P_{\text{air,max}}\) is the schedulable capacity of the air-conditioning load.
4. Case study

4.1. Example Description
In this paper, IEEE 33-node system shown in Figure 2 is used to simulate the proposed two-stage scheduling strategy, three micro-grids and five air-conditioning load nodes are added to the original distribution network system. The scheduling strategy proposed in this paper needs the support of hardware, so it is assumed that the air conditioning loads are all connected with controllers and controlled by the LA.

![Figure 2. IEEE 33-node test system](image)

4.2. PV absorption Strategy in micro-grid.
Taking the micro-network of node 8 as an example, there are three air-conditioning LAs with the maximum schedulable capacity of 2MW participating in the PV absorption.

Assume that the micro-grid operator determines that the PV that required to be absorbed for 6 periods from 12:00 to 12:30 is 4447.12, 6154.95, 6607.81, 6340.29, 6962.31 and 6203.53kW respectively according to the analysis of historical load data and PV data. The coefficients of market price are: \(a = \$0.572/\text{kW} \cdot \text{h}, b = \$0.013/(\text{kW} \cdot \text{h})^2\). The prices compensated to users by each air conditioning LA are $0.152, $0.228 and $0.380/\text{kW} \cdot \text{h}$ respectively.

Table 1 shows the PV absorption of three LAs bidding in six periods after the game. As can be seen from Table 3, the total bidding amount of the three LAs gradually increased from 3507.65kw in time period 1 to 3663.52kw in time period 3, and then gradually decreased to 3519.04kw in time period 5. Due to the fluctuation of PV power, the bidding amount in time period 6 increased slightly compared with time period 5. The bidding amount is in line with the planned amount, in other words, the higher the capacity for LAs to participate in PV absorption is, the greater the LA bidding amount is.

| Period | Bidding results (kW) | Total bidding amount (kW) | PV absorptivity | Market price ($/kW-h) |
|--------|----------------------|---------------------------|-----------------|----------------------|
|        | A        | B        | C         |                        |                       |
| 1      | 1262.55  | 1157.93  | 1087.16   | 3507.65               | 78.87%                | 1.793                |
| 2      | 1264.51  | 1226.12  | 1193.12   | 3663.52               | 78.70%                | 1.861                |
| 3      | 1277.72  | 1173.11  | 1102.34   | 3553.16               | 78.82%                | 1.813                |
| 4      | 1235.84  | 1131.23  | 1060.46   | 3427.52               | 78.97%                | 1.759                |
| 5      | 1266.35  | 1161.73  | 1090.96   | 3519.04               | 78.86%                | 1.798                |
| 6      | 1326.40  | 1221.79  | 1151.02   | 3699.21               | 78.66%                | 1.876                |

On the other hand, since the LA A has the lowest compensation price for the air-conditioning users and the highest unit profit under the same market price, the bidding amount will be more than other LAs to obtain the maximum profit. At the same time, due to the inverse ratio between the compensation price of LAs and the PV absorptivity, when the PV absorptivity is higher, the market price will be lower, which effectively reduces the compensation cost of micro-grid operators.

From the above analysis, it can be seen that the LA take part in the micro grid PV absorption in the way of non-cooperative game, and the micro-grid operators guide each air conditioning LA to participate in the day ahead bidding through the market price, which will not only help to improve the effect of PV absorption and maximize the profit of each LA, but also helps to reduce the cost of micro-grid operators.
The bidding results of node 18 and node 33 can be obtained in the same way, which will not be described in this section.

4.3. voltage control of distribution network layer

4.3.1. results of voltage control. From the analysis in the above section, it can be seen that during the period from 12:00 to 12:30, although some PV power has been absorbed in micro-grid after the day-ahead bidding, due to the limitations of the micro-grid itself, the PV power cannot be completely absorbed, and a small amount of PV power is transferred to the distribution network, as shown in Table 2. As the distribution network cannot absorb the remaining PV power naturally, voltage goes beyond the limit at some nodes, which affects the stability of the system. Using the control strategy proposed in the paper, the air conditioning load of each load layer is required for voltage control, and each adjustment period is 5min. The compensation price of the grid company to the LA is 0.3125 $/kW·h. The amount of adjustment of each user is shown in Table 5, where the negative value means to reduce the air conditioning load, and the positive value means to increase the air conditioning load. The voltage amplitude (per-unit value) of each node of the distribution network before and after the adjustment is shown in Figure. 3.

![Figure 3. The voltage of each node before and after the regulation](image)

As can be seen from Figure 3(a), due to PV power is transferred to the distribution network, voltage goes beyond the limit at node 17 and node 18 at 12:00. In order to ensure the safe operation of distribution network, some measures must be taken to maintain the voltage stability. When the strategy proposed in this paper is adopted, the voltage of each node is regulated within an allowable range of 0.97 p.u. to 1.03 p.u. However, in the second regulation period, due to the increase of the reverse power of the micro-grids, after the first regulation period, the voltage of node 18 still goes beyond the limit, so the air-conditioning load needs to continue to participate in the regulation. However, since the schedulable capacity of the air-conditioning load at node 32 is insufficient, the amount of adjustment is mainly supplied by node 16. In the third period, the reverse power of each micro network node becomes smaller. As the air conditioning load participated in the voltage control in the first two periods, the load became larger, and voltage goes below the limit at nodes 28–33. After adopting the strategy proposed in this paper, the voltage of each node can also be regulated within the safe voltage range. After the third period of regulation, there is no problem of voltage over-limit in the rest period, so the air conditioning load is not needed to participate anymore, so the article will not describe it.

It can be seen from Table 3 that the amount of adjustment is mainly supplied by node 32 which is closest to the end of main feeder. However, due to the limit of the schedulable capacity of node 32, after reaching the upper limit of schedulable capacity, the remaining power adjustment is supplied by node 16.

| Node number | Reverse power (kW) | Reverse power (kW) | Reverse power (kW) | Reverse power (kW) | Reverse power (kW) | Reverse power (kW) |
|-------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 8           | 939.47            | 991.43            | 954.64            | 912.76            | 943.27            | 1003.33           |
| 18          | 1313.47           | 1544.57           | 1204.52           | 1271.20           | 1293.27           | 1233.28           |
| 33          | 1539.52           | 1561.43           | 1242.14           | 1325.26           | 1325.77           | 1278.53           |
Table 3. The active power when voltage beyond limits occurred and the amount of adjustment of participants in the regulation

| Node number | Installed capacity | Active power(kW) | Active power regulation(kW) |
|-------------|-------------------|-----------------|---------------------------|
|             |                   | 1   | 2   | 3   | 1   | 2   | 3   |
| 9           | 1MW               | 154.05 | 154.05 | 154.05 | / | / | / |
| 14          | 1MW               | 154.05 | 154.05 | 154.05 | / | / | / |
| 16          | 1MW               | 154.05 | 252.49 | 522.66 | 98.44 | 270.17 | / |
| 21          | 1MW               | 154.05 | 154.05 | 154.05 | / | / | -154.05 |
| 32          | 1MW               | 154.05 | 1000 | 1000 | 845.95 | / | -249.01 |

4.3.2. Economic Analysis. Because the voltage control is mainly controlled by the grid company, the paper chooses the total regulation cost of the grid company and the distribution network loss as the index for economic analysis. In order to ensure the safety and stability of network, "light abandonment" is required without air-conditioning, and the price is $0.3/kW·h. The economic analysis is shown in Table 4.

Table 4. Economic analysis

| Period | Light abandonment (kW) | Network loss(kW) | Adjustment cost |
|--------|------------------------|------------------|----------------|
|        |                        | Before regulation | After regulation | With air-conditioning | Without air-conditioning |
| 1      | /                      | 745.60           | 162.18          | 120.59                | $24.59                  | $36.94                  |
| 2      | /                      | 990.61           | 144.85          | 126.93                | $7.04                   | $44.08                  |
| 3      | /                      | 641.57           | 106.14          | 100.64                | $10.50                  | $27.09                  |

It can be seen from Table 4 that the network loss is reduced after adopting the strategy proposed in the article before and after the three periods of regulation. In addition, due to making full use of the schedulable capacity of the air conditioning load, the phenomenon of "light abandonment" is avoided, and the adjustment cost of the grid company is also reduced.

In summary, the proposed strategy can not only ensure the stability of distribution network system, reduce the network loss and solve the problem of distribution network voltage beyond the limit, but also reduce the adjustment cost of the grid company and has high economic efficiency.

5. Conclusion
This paper proposes a two-stage scheduling strategy of air-conditioning load participating in PV absorption of distribution network, establishes a PV absorption model of air-conditioning load participating in the micro-grid, and makes use of air-conditioning load to participate in the voltage regulation of the grid. The conclusions of study are as follows:

1) Air-conditioning LAs take part in PV absorption in micro-grid in the way of non-cooperative game, which can not only maximize the profit of each aggregator, but also helps to reduce the cost of micro-grid operators;

2) Air-conditioning load participates in voltage regulation of distribution network, which can not only reduce the adjustment cost of the grid company, but also optimize the power flow and reduce the network loss;

3) The voltage control strategy of air-conditioning load based on MPC method can dynamically regulate the voltage based on the real-time power flow information and the status of air-conditioning load in the system, which is more reasonable than open-loop control.

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