Research on the development of distributed power generation strategy through differential scheduling requirements

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Abstract. The development of high-penetration photovoltaic power generation is an important measure to realize the energy revolution. With the continuous increase of photovoltaic capacity, the electricity generated by distributed photovoltaic can’t be absolutely integrated to power grid in the future. It is necessary to improve the scheduling requirements for photovoltaic equipment so that the system can be in safe operation. First of all, four scheduling requirements are set for the grid integration of photovoltaic equipment from the perspective of grid scheduling, which is characterized by differentiated scheduling of power and electricity between the micro-grid composed by photovoltaic equipment, energy storage and utility. Then, the capacity optimization planning model of the photovoltaic and energy storage system is established with the minimum power supply cost of the microgrid as the objective function. Finally, through the case study, it is found that industrial and commercial enterprises have the economic motivation to invest in the construction of the photovoltaic and energy storage microgrid, which will strengthen confidence in promoting the rapid development of photovoltaic power generation.

1. Introduction

The energy revolution is a major measure to achieve sustainable development. In order to achieve the goal of carbon neutrality by 2060 in China [1], it is necessary to vigorously develop renewable energy power generation such as solar photovoltaic (PV). China is rich in solar energy resources, and there are sufficient potential PV installation sites. PV power generation has and will continue to develop rapidly.

PV power generation is intermittent, variable and uncertain [2], and cannot supply power to the load alone. In the initial stage of PV development, PV installed capacity accounted for a relatively low proportion, and peak regulation capacity of grid is rich. The fluctuating PV electricity can be fully consumed by the grid. However, as the capacity of PV power integration increases, the ratio of electricity generated by PV systems to the total load is rapidly increasing. After the fluctuating PV power is consumed by the grid, it faces many major challenging problems such as over-limit node voltage and balance difficulty of peak-to-valley power in operation. In order to cope with the volatility of PV output, the grid's scheduling requirements for PV equipment will be gradually increased. In addition, as the cost of equipment continues to decrease, wind and PV power sources will be supplemented with a certain capacity of energy storage (ES) in the future.

There is substantial research on the planning of equipment capacity in distribution networks and microgrids. The off-grid PV and ES system was as the research object in the literature [3]. The research on capacity optimization planning of equipment considering the reliability of power supply...
was carried out, the key of which was determining power supply sequence of power sources. The capacity optimization planning of wind-PV-thermal bundling operation mode was carried out in the literature [4], and the total social cost of unit electricity was mainly analyzed. The oversizing coupled with proactive curtailment of PV equipment was analyzed in the literature [5]. The more economical result could be obtained when PV electricity curtailment is allowed, but of which the load was assumed to be constant or the history electricity consumption data of Minnesota State. The capacity configuration function of ES equipment was proposed based on the short-term forecast error of PV output and load in the literature [6]. The centralized and distributed configuration schemes were respectively explored. From the view of power system planning, dispatch, and control, the impact of large-scale PV integrated to the grid on the steady-state and dynamic characteristics of the power system was discussed in the literature [7]. An optimization method for the installed capacity of an independent wind-PV system was proposed and the complementary effects of wind and PV capacity on reducing power supply costs were also analyzed in the literature [8].

High penetration of wind generation in electrical microgrids causes fluctuations of tie-line power flow and significantly affects the power system operation. A framework is proposed to jointly perform Optimal Generation Scheduling and optimal Distribution Feeder Reconfiguration on a day-ahead time frame in the literature [9]. In order to preserve system reliability during on-peak periods, Demand Response program is also implemented using Time of Use energy tariffs and reducible loads to change energy consumption patterns of consumers in the literature [10]. A major limitation of multi-area economic/environmental dispatch problem is the capacity of tie lines. A decentralized methodology is proposed for optimal scheduling generation units taking into consideration environmental constraint [11]. The challenges and advantages of having sections of a power distribution system constituted by networked microgrids to efficiently manage distributed energy resources were presented, in particular roof-top solar photovoltaic and battery energy storage systems in the literature [12]. A novel approach able to adapt to a given PV generation and load demand and individually control the battery and the net grid energy, was presented in the literature [13].

In summary, the existing research is often carried out from the perspective of satisfying given load by power sources configuration and improving the reliability of electrical power system. The requirements of scheduling system for power sources equipment are often ignored, and with the gradual increase of the grid-integrated capacity of PV equipment, the scheduling requirements of the grid will be improved accordingly. In view of the shortcomings of existing research, differentiated grid scheduling requirements for the grid integration scenarios of PV equipment are proposed in this paper. Capacity optimization planning from the perspective of power supply is carried out economically. First, four scheduling requirements for PV power generation are set, namely the active distribution network scenario, the limited grid connection scenario where the tie-line capacity is greater than the maximum load, the limited grid connection scenario where the tie-line capacity is less than the maximum load, and the microgrid scenario where the algebraic sum of power exchange with grid is zero. The scheduling requirements of PV electricity integrated to the grid are gradually stricter and stricter. Then, in accordance with the principle of use for self-generation, purchase if electricity shortage occurs, and sale of surplus electricity, the operation constraints of PV and ES equipment under differentiated scheduling requirements are proposed. An optimization planning model is established, and the reliability cost of power supply is taken into account. Finally, Combining the cost change trend of core parameters such as the price changing trend of PV and ES equipment, the grid parity analysis of various evaluation scenarios is carried out, and then PV investment recommendations and policy recommendations to promote the development of PV power generation are given.

2. Four scheduling requirements for PV power generation

The microgrid is constituted by PV and ES equipment, which are integrated to the utility through tie-line, as shown in Figure 1. Next, four scheduling requirements for PV power generation are given by analyzing the relationship between the tie-line capacity and the load in the microgrid.
2.1. *Active distribution network scenario*

Only PV equipment is invested in the scenario. The PV equipment is integrated to the bus bar in multiple ways, and then integrated to utility through chopper and inverter equipment. PV electricity is directly integrated to the local distribution network and supplies to the load. The power demand of the distribution network is large, and the scheduling system has no special requirements for PV power integrated to the grid through tie-line. The electricity generated by PV is supplied to the load firstly. If there is surplus electricity, it will be sold to the utility. When the installed capacity of PV equipment is less than the capacity of the tie-line, the electricity generated by PV is 100% consumed.

2.2. *Limited grid connection scenarios where the capacity of the tie-line is greater than the maximum load*

PV and ES equipment is built on the microgrid at the same time. PV equipment is integrated to the bus bar in multiple ways and has a simple parallel connection relationship with ES. Then it is integrated to the utility through chopping and inverter equipment and supplies power to the load. When the active power output of PV equipment is large, the user’s own load is firstly supplied, and the surplus power is charged to the ES. If there is still surplus power, it is sold to the grid. When the active output of PV equipment is small and the shortage of power occurs, the load is firstly supplied by ES. If there is still a shortage of power, the electricity shortage will be bought from the utility. The capacity of the tie-line is greater than the maximum load in the microgrid, that is, the load demand in the microgrid can be satisfied if equipment failure of tie-line does not occur. The ES equipment is not charged through the utility. There is no requirement for sale of surplus electricity and purchased electricity from utility.

2.3. *Limited grid connection scenarios where the capacity of the tie-line is less than the maximum load*

Consider the construction of PV and ES equipment in the microgrid. The operating of the microgrid is the same as the second scenario. The tie-line capacity is less than the maximum load in the microgrid. When power shortage occurs due to insufficient power supply, the reliability cost is calculated by the user power loss index [14].

2.4. *The microgrid scenario where the algebraic sum of power exchange with grid is zero*

Consider the construction of PV and ES equipment in the microgrid. The operating logic of the microgrid is the same as in the second scenario. The capacity of the tie-line is less than the maximum load of the microgrid, and the computing of reliability cost is the same as the third scenario. The algebraic sum of annual power exchange is zero, that is, the total amount of electricity purchased from the grid through the tie-line and the total amount of electricity sold to the grid through the tie-line each year in the microgrid is the same.
3. PV and ES system capacity planning model considering scheduling requirements

3.1. Cost composition and calculation method

The cost of power supply cost in the microgrid includes: ① the investment in PV and ES system equipment. ② the purchase cost of power shortage and benefit of selling surplus power. ③ the loss caused by power shortage.

(1) Equipment investment

The investment in PV and ES equipment is a one-time investment. The average annual investment cost of PV and ES equipment is calculated through the equal annual value analysis method:

\[
C_{eq} = \frac{(1 + I)^Y}{(1 + I)^Y - 1} C_{PV} + \frac{(1 + I)^Y}{(1 + I)^Y - 1} C_{ES} \times k_{om1} \times k_{om2} \times I \times C_{eq} \times Y_1 + Y_2
\]

Among which, \( C_{PV} \) denotes the PV cost of unit capacity investment, yuan/kW. \( P_{PV} \) denotes the planning capacity of PV, kW. \( C_{ES} \) denotes the ES cost of unit capacity investment, yuan/kWh. \( E_{ES} \) denotes the planning capacity of ES, kWh. \( Y_1 \) and \( Y_2 \) respectively denote the life of PV and ES investment. \( I \) denotes the discount rate of bank. \( C_{eq} \) denotes the equal annual value cost of investment in the microgrid.

(2) Cost of purchase/benefit of sale

When the supply and demand in the microgrid cannot be self-balanced, cost of purchase from the grid and benefit selling electricity to the grid through the tie-line are calculated as follows.

\[
C_{ex} = p_{buy} \times \int_{t=1}^{N_t} \max \{P_{tie,t}, 0\} dt + p_{sell} \times \int_{t=1}^{N_t} \min \{P_{tie,t}, 0\} dt
\]

Among which, \( p_{buy} \) denotes the electricity price purchasing from grid. \( p_{sell} \) denotes the electricity price selling to grid. \( P_{tie,t} \) denotes the power on tie-line at the \( t \)th time. The direction of the flow from the grid to the microgrid is taken as positive. \( N_t \) denotes the simulation period, \( N_t \) is equal to 1 year in this paper. \( C_{ex} \) denotes the cost/benefit of purchase/sale in the microgrid.

(3) Loss of power shortage

When the capacity of the tie-line is less than the load in the microgrid, there is a risk of lack of electricity. The loss of power shortage is calculated by the following formula.

\[
C_{re} = C_{unse} \times \int_{t=1}^{N_t} P_{load,t} - P_{PV,t} - k_{st} \times P_{st,t} - P_{tie,t} dt
\]

Among which, \( C_{unse} \) denotes the loss caused by power shortage, taken as 100 yuan/kWh in this paper [9]. \( P_{load,t}, P_{PV,t} \) and \( P_{st,t} \) respectively denote the active power of load, the active output of PV and discharge power of ES at the \( t \)th time in the microgrid. \( k_{st} \) denotes the charging and discharging efficiency of ES equipment. \( C_{re} \) denotes the loss caused by power shortage.

3.2. Capacity planning model of PV and ES system

The original load in the microgrid obtains electricity from the utility. Power supply cost is reduced by investing PV and ES equipment. To achieve the lowest total cost is taken as the objective function of the optimization model:

\[
\min C_{to} = C_{eq} + C_{ex} + C_{re}
\]

The state of the stored energy in the ES equipment in the microgrid is denoted by the state of charge:

\[
S_t = \frac{E_{st,t}}{E_{st}} \times 100\%
\]

Among which, \( E_{st,t} \) denotes the amount of stored energy in the ES equipment at the \( t \)th time. \( S_t \) denotes the charging state index of ES equipment at the \( t \)th time.
\[
\begin{align*}
S_{lo} &\leq S \leq S_{up} \\
-P_a &\leq P_{st} \leq P_a \\
-P_{tie} &\leq P_{tie} \leq P_{tie} \\
0 &\leq P_{PV,j} \\
\end{align*}
\] (6)

Among which, \(S_{lo}\) and \(S_{up}\) denote the charging state upper and lower limits of ES equipment. \(P_{st}\) denotes the maximum charging and discharging power of ES equipment. \(P_{tie}\) denotes the rated capacity of tie-line. \(P_{PV,j}\) denotes the maximum active output of PV equipment without electricity curtailment generated by PV equipment at the \(t_0\) time.

The optimization area composed by PV and ES equipment capacity is determined as follows. The minimum installed capacity of PV equipment is 0, and the maximum installed capacity is set to 3 times larger than the annual electricity consumption in the microgrid:

\[
P_{PV,max} = 3 \times \frac{\int_{t_1}^{t_N} P_{load,j} dt}{T_{PV}}
\] (7)

Among which, \(T_{PV}\) denotes annual utilization hours of PV equipment without electricity curtailment. \(P_{PV,max}\) denotes the maximum installed capacity of PV equipment. The minimum installed capacity of ES equipment is zero, and the maximum installed capacity is set as average weekly electricity consumed by users.

\[
E_{st,max} = 7 \times \frac{\int_{t_1}^{t_N} P_{load,j} dt}{365}
\] (8)

Among which, \(E_{st,max}\) denotes the maximum installed capacity of ES equipment.

In order to solve the above optimization planning model, it is not difficult to find from (1) to (6) that the power supply cost of the microgrid needs to be calculated. \(P_{tie,j}\), \(P_{load,j}\), \(P_{PV,j}\), and \(P_{st,j}\) in the simulation period are determined. According to the electricity dispatch priority of the 4 scenarios described in section 2, the unit power supply cost of microgrid is calculated by simulation.

\[
C_{kWh} = \frac{C_{in}}{\int_{t_1}^{t_N} P_{load,j} dt}
\] (9)

The optimal scheme of PV and ES system is determined according to \(C_{kWh}\).

3.3. Solution method

The specific scenarios are simulated using Matlab. The detailed steps are as follows:

Step 1: Input load data and investment cost of PV and energy storage equipment.

Step 2: Determine the optimization two-dimensional area composed of the PV and energy storage capacity.

Step 3: Perform the simulation with capacity combination of the PV and energy storage, and calculate the cost of unit electricity according to the stimulation result.

Step 4: Output the optimal capacity combination of the PV and energy storage.

4. Case study

The factory building roofs of industrial and commercial enterprises are ideal installation places for PV equipment. At the same time, industrial and commercial enterprises have high electricity consumption and high electricity purchase cost, which are the most suitable place to invest microgrids constituted by PV and storage system. The research on microgrid capacity planning for industrial and commercial enterprises is carried out in this paper. The maximum load of a certain industrial and commercial enterprise is 1MW, and the time-series data of load adopts the recommended parameters of the IEEE RTS system [15]. The capacity of the tie-line in the four scenarios is shown in Table 1, and other parameters are shown in Table 2.
Table 1. The related parameter in the four scenarios.

|                     | the 1st scenario | the 2nd scenario | the 3rd scenario | the 4th scenario |
|---------------------|------------------|------------------|------------------|------------------|
| \( P_{\text{tie}} \) (MW) | 100              | 2                | 0.8              | 0.8              |

Table 2. Operation evaluation parameters.

| \( C_{\text{PV}} \) (in 2020) | \( Y_1 \) | \( C_{\text{st}} \) (in 2050) | \( Y_2 \) | \( k_{\text{st}} \) | \( p_{\text{buy}} \) | \( p_{\text{sell}} \) | \( I \) |
|------------------------------|----------|-----------------------------|----------|-----------------|----------------|----------------|------|
| 4500                         | 25       | 1800                        | 15       | 95%             | 0.8            | 0.38           | 6%   |
| 2000                         | 25       | 800                         | 15       | 95%             | 0.8            | 0.38           | 6%   |

Table 3. Optimization results of 4 scenarios.

| index | PPV | Est | CkWh |
|-------|-----|-----|------|
| the 1st scenario | 2020 | 6.2 | 0.62 |
|         | 2050 |     |      |
| the 2nd scenario | 2020 | 4.3 | 0.63 |
|         | 2050 | 9.9 | 0.34 |
| the 3rd scenario | 2020 | 3.3 | 0.73 |
|         | 2050 | 7.7 | 0.45 |
| the 4th scenario | 2020 | 7.3 | 0.90 |
|         | 2050 | 6.18 | 0.46 |

The evaluation results of the four scenarios are shown in Table 3. It is not difficult to find:

1. In Scenario 1, when the unit capacity cost of PV is 4500 yuan/kW, the unit cost per kilowatt-hour electricity generated by PV equipment is 0.41 yuan/kWh, which is higher than \( p_{\text{sell}} \). Therefore, selling electricity does not bring benefits, but it is obviously lower than \( p_{\text{buy}} \). So the purpose of reducing power supply costs can be achieved by use electricity generated by oneself. When the PV cost drops to 2,000 yuan/kW, the unit cost per kilowatt-hour electricity generated by PV equipment is 0.18 yuan/kWh, and enterprises can obtain high benefits from selling electricity to the grid through the tie-line, and the larger the PV installation capacity, the more benefit can be obtained.

2. In Scenario 2, \( C_{\text{kWh}} \) becomes 0.63 yuan/kWh, which is obviously lower than \( p_{\text{buy}} \). Enterprises still have incentives to install distributed PV systems, and as the investment cost of PV and ES systems decreases, enterprises will have incentives to install certain capacity of ES equipment. The trend of \( C_{\text{kWh}} \) with \( P_{\text{PV}} \) and \( E_{\text{st}} \) is shown in Figure 2. Within the two-dimensional optimization area composed of energy storage and PV installed capacity, coordinates of the point with the lowest cost of power supply is the best installed capacity combination of energy storage and PV. The optimal cost of unit electricity is decreased to 0.34 yuan/kWh.

Figure 2. Schematic diagram of connection between microgrid constituted by PV, ES and utility.
(3) In scenario 3, the reliability cost in 2020 is 465,670 yuan, so $C_{kWh}$ is higher than that in scenario 2, but still lower than $p_{buy}$. Enterprises still have incentives to install distributed PV systems, furthermore they will have incentives to install certain capacity of ES equipment in 2050. The installed capacity of ES in 2050 is 7.3 MWh, which is increased compared with scenario 2.

(4) In Scenario 4, the grid exchange power between the grid and the user is zero, and the user is basically self-sufficient. Although it will be higher than $p_{buy}$ in 2020, it will be significantly lower than $p_{buy}$ in 2050. At this time, the power grid is only responsible for auxiliary peak shaving. It is not difficult to find that the $C_{kWh}$ is very close to scenario 3.

5. Conclusions

The capacity optimization planning research on photovoltaic and energy storage systems is conducted in this paper from the perspective of safe operation of power systems. First of all, four scheduling requirements are set for the integration of photovoltaic equipment, which denote four scenarios that may appear as the penetration rate of photovoltaic power increases in the future. Then, a capacity optimization planning model is established and the cost of equipment, electricity purchase and reliability and benefit of selling are taken into account. Finally, a case study is carried out, and it is found that industrial and commercial enterprises have the economic motivation to invest in the construction of microgrids composed by photovoltaic and energy storage equipment, and as the cost of equipment continues to drop, energy storage equipment will be invested. In view of the peak shaving problems caused by the widespread integration of distributed generators to the distribution network, reliability of power system will be obviously improved by installing a certain capacity energy storage.

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