Research of Economic Operation and Control Strategy for PV-Storage-Charging Integrated Power Station

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Abstract. This paper proposes an economic operation mode and control strategy for an PV-storage-charging integrated power station. By optimizing the capacity configuration and analyzing the mechanism relationship of its various operating modes, this paper establishes the system model including PV system power, energy storage SOC and charging spot power, and gives its economic operation constraints. Based on statistical analysis of historical data, the strategy optimizes the operation mode dynamically to control the grid power flow and balance the system power supply and load. Simulation results verify the economic and stable operation of this strategy.

1. Introduction
‘The Outline of the Thirteenth Five-Year Plan for National Economic and Social Development of the PRC’ [1] clearly announce that “Promoting the construction of demonstration projects for energy storage power stations and strengthening the integration and complementation of multiple power sources and energy storage facilities” will be major projects for energy development. In 2015, the investment scale of China’s charging and discharging integrated charging station was 1.15 billion yuan and it is expected to reach 10.37 billion yuan by 2020. Benefiting from the continuous decline of chemical energy storage costs and the technological progress, the total capacity of new energy storage projects and their installed capacity is expected to increase several times in recent years. The rapid development of the energy storage industry has made the prospective PV-storage-charging market popular among industry players. At the same time, with the introduction of the local subsidy policy for energy storage, the industry's attention to the PV-storage-charging integrated power station project and capital investment have been continuously improved, which will help the business model of PV-storage-charging integrated power station to achieve a substantial breakthrough. The PV-storage-charging integrated power station has a small footprint, diversified functions and low operating costs. Compared with ordinary electric vehicle charging stations [2], it has many advantages. It can build a large-capacity charging station without modifying the power grid to realize integration of photovoltaic, energy storage and EV charging. The integrated power station can not only delay the expansion planning requirements of the grid to access the charging load of electric vehicles, but also stabilize the randomness of charging load and improve the reliability of grid operation. At the same time, it promotes the near-end consumption between electric vehicle and distributed renewable power for low carbon development. However, with the large-scale construction and development of PV-storage-charging integrated power station, the grid operation faces new problems and challenges. On the one hand, photovoltaic power generation is greatly affected by the climate environment and can only work during the day, which has a greater impact on the stable operation of the system. It has aggravated the demand for adjustable energy in grid operation. On the other hand, energy storage equipment has flexible and controllable operation mode, which can provide diversified coordination and optimization space for grid operation.[3]
Along with the evolution of energy supply and demand side changes and the rapid promotion of the PV-storage-charging integrated power station project, the photovoltaic power generation system, the energy storage system and the charging system are organically combined to enhance the grid's consumption of renewable energy.[4] The key issues for all grid companies are how to improve the ability of grid operation reliability and economy, reduce project investment and operation costs and obtain a wider range of resources to optimize configuration and operational efficiency.

2. Structure and Composition
PV-storage-charging integrated power station mainly includes power supply and distribution units, photovoltaic units, energy storage units, charging units and monitoring management units.[5] The system structure is as shown in Figure 1:

2.1. Power supply and distribution units
Power supply and distribution units provide the required power not only for the EV charging station, but also for the lighting and control equipment such as monitor and compensation equipment in the power distribution.

2.2. Monitor management unit
It can handle comprehensive data processing, program development, issue command and micro-grid operation mode switching.[6] By obtaining various parameters and processing comprehensive data of photovoltaic inverters and load nodes, formulating strategies of photovoltaic switching mode, power output adjustment and circuit breaker control, this unit achieves photovoltaic, energy storage, loads real-time control and manage the operation of integrated power station.

3. Economic Operation Analysis
In this paper, the maximization revenue of PV-storage-charging integrated power station is the optimization goal. Take real-time power balance of the integrated power station, the output power of photovoltaic, the charging and discharging power of the energy storage unit and the state of charge as the constraints. Also considering the battery cost of the energy storage unit, this paper establishes an economic operation analysis model for PV-storage-charging integrated power station.[7]

3.1. Constraints of PV-storage-charging integrated power station
3.1.1. Real-time power balance constraint. \( P_z(t) \) is the power delivered from the public power grid to the power station at time \( t \); \( P_g(t) \geq 0; P_g(t) \) is the power delivered from station to the public grid at time \( t \); \( P_{bat}(t) \) is the charge or discharge power of the energy storage unit at time \( t \). \[ P_z(t) - P_g(t) = P_{bat}(t) + P_{ev}(t) - P_{pv} \] (1)

3.1.2. Photovoltaic output constraint. \( P_{pv,\text{max}} \) is maximum photovoltaic power:
\[ |P_{pv}(t)| \leq P_{pv,\text{max}} \] (2)

3.1.3. Charge and discharge of energy storage constraint. \( P_{bat,\text{max}} \) is maximum of energy storage.
\[ |P_{bat}(t)| \leq P_{bat,\text{max}} \] (3)
3.1.4. Constraint of state of charge for Energy storage. $SOC(t)$ is the battery charging condition of the energy storage unit battery at time $t$. $SOC_{min}$ is the lower limit of and $SOC_{max}$ is the upper limit of SOC of the energy storage unit.

$$SOC_{min} \leq SOC(t) \leq SOC_{max}$$  \hspace{1cm} (4)

3.2. Revenue objective function of PV-storage-charging integrated power station

The daily revenue calculation formula of PV-storage-charging integrated power station is:

$$E = \sum_{t=1}^{24} (m_z(t) \cdot P_z(t) - m_g(t) \cdot P_g(t)) \Delta t$$  \hspace{1cm} (5)

In formula (5): $E$ is the total daily income of the power station, $m_z(t)$ is the price of residual electric energy sold to power grid, $m_g$ is the price of electric energy buy from power grid. $\Delta t$ is the power data acquisition interval, usually at 15 min.

Under the premise of satisfying the internal load demand of the power station, the surplus power of the photovoltaic power generation unit can send to the public grid. The electricity stored in the energy storage unit can be supplied by photovoltaics or from the public grid. However, for economic reasons, the electricity stored in the energy storage unit can only be supplied to the internal power storage load of the integrated power station, and is not allowed to be transported to the public grid.

3.3. Simulation Analysis Parameters

The main key factors for the economic operation of the optical storage and charging integrated power station include three parts: photovoltaic unit output, electric vehicle charging load and electricity purchase price from the public grid. Simulation analysis based on the three factors as basic parameters.

3.3.1. Photovoltaic unit output parameters. The output of photovoltaic units is an important factor in the economic operation of an integrated power station. Due to the randomness of photovoltaic power generation, this paper simulates the photovoltaic power generation data of the production base microgrid project (The project has been put into operation for 608 days. The installed capacity of photovoltaic power generation unit is 110kWh) and selects three different light intensity scenes to analysis the output of photovoltaic unit.[9] The curve in Figure 2 show the photovoltaic power generation change with time in three scenarios. Among them, scene 1 is the photovoltaic output curve under daily conditions; Scene 2 is the photovoltaic output curve under the condition of strong light intensity; Scene 3 is the photovoltaic output under the condition of weak light intensity.

![Figure 2. Photovoltaic output scene](image1)

3.3.2. Electric vehicle charging load parameters: The electric vehicle charging load parameters are obtained by referring to the actual operating data of the Wenyang charging station. A total of eight 60kW DC charging piles are installed in the station and mainly provide charging services for electric buses. After investigation and statistics, the current electric bus has a long distance of 25-50 kilometers per journey and the battery capacity is less than 100kWh. Therefore, every time the buses return to the site, they need to charge it in time. There is a certain charging demand during the peak electricity period at a high electricity price. This paper takes twice the actual total load of the station as
3.3.3. The price of purchase electricity: The integrated power station electricity purchases price from the public power grid refers to the sales price list of Shandong Power Grid in 2019 as shown in Figure 4. The price of surplus electricity sent to the grid accord to the price policy of 2018 photovoltaic power generation project. The total electricity subsidy standard of distributed power generation which in “spontaneous use and surplus online” mode is 0.37 yuan per kWh.

3.3.4. Simulation results and analysis. According to the simulation model established above, the optimization algorithm is solved by Matlab + Yalmip + Cplex.[10] as shown in Figure 5. Operation of the integrated power station, the charging and discharging power of the energy storage unit and the exchange power curve between the power station and the public power grid in the three scenarios are as Figure 6, 7 and 8:

In the three scenarios, the energy storage power is positive for charging, and the negative is for discharging; the positive switching power indicates that the public power grid delivers electrical energy to the integrated power station. The negative means integrated power station delivers electrical energy to the public power grid. Analysis and optimization results show that electric vehicles need power at night and its charging load is large while photovoltaic output is zero. The public grid is responsible for power supply at this period and electricity price is at low valley. Energy storage system is also charging at this time. When in the
daytime, the electric vehicle charging demand is large too but photovoltaic power generation also rises to a higher level. Because price of electricity purchased from the public grid is high, use photovoltaics first to meet the changing needs. The shortage is met by the discharge of the energy storage system, surplus electricity charges the energy storage system or transport into the public grid if there is. At the condition of the electric vehicle charging load buy from the public grid, compare the changing cost under different PV intensity scenarios, as shown in Table 1.

### Table 1. the cost of purchase electricity in different scenes and the scene of No-PV

| (yuan/day) | Purchase electricity from public grid(No-PV) | Scene 1 (normal sunshine) | Scene 2 (weak sunshine) | Scene 3 (strong sunshine) |
|-----------|---------------------------------------------|---------------------------|-------------------------|--------------------------|
| Purchase  | 2504.7                                      | 945.6                     | 1806.2                  | 757.1                    |

As can be seen from the above table, in three different PV scenarios, by optimizing the operation strategy, the cost of purchasing electricity at daytime is significantly reduced. Especially, under the condition of strong light intensity, the cost of purchasing electricity at daytime is relatively obvious. In this case, the electric vehicle charging load level is higher during the daytime, and most of the photovoltaic power generation is used to supply the charging load, and the surplus part can also be stored in the energy storage unit. The energy storage unit can also store power at the low-cost time of power grid. The electric energy is used to meet the charging load demand during the high electricity price period, and the peak-valley spread benefit is obtained.

Considering the peak-valley electricity price period and charging load demand, optimizing the configuration and operation strategy of the integrated power station can realize effective management and scheduling of the energy storage unit, save a large amount of electricity purchase cost and bring considerable economic benefits.

### 4. Research of Control Strategy

In the field of PV-storage-charging research, the most critical is the control strategy. The basic requirements are: the access of any device must not have a significant impact on the existing PV-storage-charging system; it can coordinate the generation and load of the system and choose independently work mode; it can run stably in grid integration and grid separation, also smoothly switch between the two modes; it can independently control active and reactive power, can adapt to the dynamic demand of the load in the PV-storage-charging system[11], and has an ability of adjusting the unbalance of system independently.

The principle of the economic operation control strategy for PV-storage-charging integrated power station is to maximize the use of photovoltaic power generation to provide electric vehicles, energy storage systems and other loads. If the power demand in the system cannot be met, the power supply is exceeded by the power grid while the surplus energy is delivered to the public grid. Ensure real-time power balance of each unit in the system, and adjust the power allocation according to the current SOC of the energy storage unit to avoid deep discharge or overcharge of the energy storage unit [12].

During the operation of the integrated power station, the power relationship within the system is as follows:

\[
R_{mg} = P_{pv} + P_{bat} - P_{load} + P_{g}
\]  \(6\)

In equation (6), \(R_{mg}\) is the power required to maintain the stability of the bus voltage. \(P_{pv}\) is the power generated by the photovoltaic unit, \(P_{bat}\) is the charging or discharging power of the energy storage unit. \(P_{bat} > 0\) indicate the energy storage discharge, while \(P_{bat} < 0\) indicate the energy storage charging. \(P_{load}\) is the system load power. \(P_{g}\) is the input power of the public power grid.

According to the energy exchange trend in the running process, the following four working modes can be divided as Figure 9, 10, 11, 12:
The coordinated control operation strategy is shown in Figure 13:

We also selected Scene 1 (normal sunshine), and analysed the cost of electricity purchase in the case of sunshine and load changes, also consider whether to run the strategy. As shown in Table 2:

| Scene | No-PV-Storage (yuan/day) | PV decline (No-Strategy) | PV decline (Strategy) | Load rise (No-Strategy) | Load rise (Strategy) |
|-------|--------------------------|--------------------------|-----------------------|-------------------------|----------------------|
|      | Original load | Load change | Original load | Load change | Original load | Load change | Original load | Load change | Original load | Load change |
| Purchase | 2413.2 | 3470.8 | 945.6 | 1178.8 | 1158.3 | 2003.6 | 1995.0 |
| Save | 0 | 0 | 1467.6 | 1234.4 | 1254.9 | 1467.2 | 1475.8 |

The establishment of the PV-storage-charging integrated power station and the benign interaction between them can save a lot of electricity purchase expenses. Even in the case of sudden changes in sunshine, load and other factors, the use of optimized operation strategies can still bring considerable benefits.

In order to achieve an economic operation goal of sufficient and reasonable using of electrical energy and avoiding waste of electricity. During the operation of the PV-storage-charging integrated power station, the photovoltaic unit generates power firstly supply the EV and then charge the energy storage unit. When the energy storage is fully charged, the surplus energy will be transferred into the public grid.[13] and the energy storage unit maintains the system power. The balance of the system is maintained by the bidirectional converter. When the inner power is insufficient, consider the charge and discharge loss of the energy storage unit and the cost of the peak-valley electricity price to decide how much the electric energy buy from the public power grid to meet the charging load of the electric vehicle and dynamically adjust charge and discharge status of the energy storage unit.
5. Conclusions
In this paper, PV-storage-charging integrated power station is analyzed under different PV output scenarios and an economic operation optimization model of integrated power station is established. According to the different working states of the system, the energy of each unit is reasonably dispatched. The coordinated operation between the grid, photovoltaic, energy storage unit and charging load is realized to achieve the goal of economic operation and minimize the cost of purchasing electricity.

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