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Research on Micro-Grid System Configuration Optimization of Photovoltaic-Battery System

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Abstract: Photovoltaic generation is a new technology, which is the most mature, fastest growing, and widely used. The rapid development of photovoltaic-battery system has put forward new requirements for the optimal configuration of power in energy system. This paper proposes a grid-connected distributed photovoltaic-battery system, and constructs an optimization model of taking into account total system cost and utilization ratio of photovoltaic-battery system. For the part of battery energy storage that has been generally ignored in previous studies, this paper adds the levelized cost of storage function by referring to the levelized cost of energy. Among the constraints of the optimization model, a more detailed and reasonable optimal scheduling scheme is proposed by considering the real-time price of grid and the charge and discharge cost of battery. Finally, the effectiveness of constraints and optimal scheduling strategy is verified by using the annual observation data of solar radiation.

Keywords: Micro-grid; Photovoltaic-battery system; Power optimization strategy; Levelized cost of storage

1 Introduction

With increasing demand for renewable energy and energy storage of consumers, the global energy market is undergoing drastic changes. A power generation system with photovoltaic-battery system (PV-B) is considered to be a technology that can reduce global greenhouse gas emissions and replace traditional energy generation. With the deepening of the research on photovoltaic-battery system, the focus of research has gradually shifted from its economic analysis to the research on photovoltaic generation and the optimal scheduling of battery. Reasonable scheduling strategy can not only improve the utilization rate of photovoltaic generation, but also save the electricity cost of users.

Nge et al.[1] proposed a real-time energy management system for rooftop photovoltaic generation system with energy storage. Connected to the smart grid, the real-time energy management system can control the photovoltaic generation and energy storage system directly according to the price signal, so as to maximize the overall revenue of the system under the condition of satisfying the energy storage constraints. Hemmati et al.[2] proposed an efficient home energy management system by utilizing energy storage battery and photovoltaic generation, and optimized the charging and discharging decisions, capacity and power of energy storage battery. Kusakana et al.[3] developed an optimal energy management model to minimize the energy cost of a microbrewery, under demand response, supplied with a grid-connected photovoltaic system with battery storage system. In order to study the impact of photovoltaic generation on residents' interests and the environment under the background of organic photovoltaics self-consumption of residential users, Marios et al.[4] combined both economic analysis and life cycle assessment to study the impact of energy storage on organic photovoltaics self-consumption of residential users.

The aforementioned studies have done a lot of research on photovoltaic generation, charging and discharging strategy optimization of battery, solar power utilization rate and electricity cost, but there are few studies on the levelized cost of storage has not been covered. Therefore, this paper adds the levelized cost of storage function by referring to the levelized cost of energy. Among the constraints of the optimization model, a more detailed and reasonable optimal scheduling scheme was proposed by considering the real-time price of grid and the charge and discharge cost of battery.

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Table 1: Energy flow power between components of photovoltaic energy storage system

$P_{PU}(t)$	Power from photovoltaic panels to residential user at time t
$P_{PB}(t)$	Power from photovoltaic panels to battery at time t
$P_{PG}(t)$	Power from photovoltaic panels to grid at time t
$P_{BU}(t)$	Power from battery to residential user at time t
$P_{BG}(t)$	Power from battery to grid at time t
$P_{GU}(t)$	Power from grid to residential user at time t
$P_{GB}(t)$	Power from grid to battery at time t

2 Grid-connected PV-B system

Grid-connected PV-B system constructed consists of photovoltaic panels, battery, load of residential users, online shopping/selling system of electricity, smart meters, controllers and inverters, etc. [5], as shown in Figure 1.

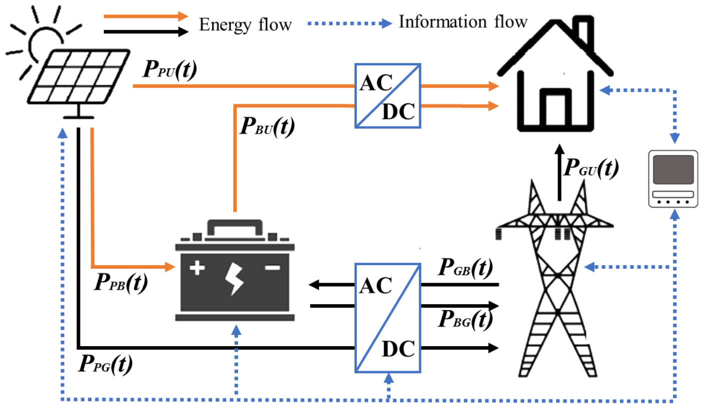

Figure 1: Grid-connected photovoltaic-battery system framework

PV-B system is connected to the load and grid through inverters, respectively. In Figure 1, the dashed two-way represent information and control flow, while the remaining arrows represent real-time power interaction among various parts. On the premise of giving priority to meet the load demand of residential users, the controller selects the optimal control strategy to adjust the system power consumption in real time according to the load demand, photovoltaic output power and electricity price information, etc., while ensuring the economy and stability.

The energy flow between the components of grid-connected PV-B system is shown in Table 1.

3 The optimization model grid-connected PV-B system

3.1 Objective function

The optimization model is divided into two parts, namely, minimizing total system cost and maximizing the utilization rate of grid-connected PV-B system. The solution of the model is constructed as a multi-objective mixed integer linear programming problem with constraints. Through comprehensive consideration of photovoltaic output, electricity price information, battery state of charge (SoC) and load demand, the energy flow between components of PV-B system is optimized, so as to minimize total system cost and maximize the purpose of the utilization rate of PV-B system.

3.1.1 Minimize total system cost

System cost includes photovoltaic generation cost, energy storage cost (charge and discharge cost), purchase / sale cost / revenue, etc.

$$\begin{aligned} Minimize\ f_1 = & \sum_{t=1}^{T} \rho(t) \left(P_{GU}(t) + P_{GB}(t)\right) + \sum_{t=1}^{T} \rho_{PV}(t) \left(P_{PU}(t) + P_{PB}(t) + P_{PG}(t)\right) \\ & + \sum_{t=1}^{T} \rho_B(t) \left(P_{PB}(t) + P_{BU}(t) + P_{BG}(t) + P_{GB}(t)\right) - \sum_{t=1}^{T} \rho_G(t) \left(P_{PG}(t) + P_{BG}(t)\right). \end{aligned} \tag{1}$$

where, the first part is the electricity purchase cost of residential users from grid, and $\rho(t)$ is the electricity price at time t. The second part is the generation cost of photovoltaic panels, which ρ_{PV} is the levelized cost of electricity of photovoltaic output power. The third part is the charge and discharge cost of battery, ρ_B is the levelized cost of storage (LCOS). The fourth part is the income of the surplus electricity, which ρ_G is the on-grid price, and its value is 0.391 yuan/kWh[6].

3.1.2 Maximize the utilization rate of PV-B system

In order to improve the stability of PV-B system and reduce solar energy waste, it is necessary to maximum use of photovoltaic generation while minimize the power interaction with grid. The second objective function is defined as:

$$f_2 = \max \sum_{t=1}^{T} \left(P_{PB}(t) + P_{PU}(t) + P_{BU}(t)\right) + \min \sum_{t=1}^{T} \left(P_{PG}(t) + P_{GB}(t) + P_{BG}(t) + P_{GU}(t)\right) \tag{2}$$

3.2 Constraints

In order to ensure the normal operation of the photovoltaic energy storage system and make the photovoltaic and energy storage work in a stable and reasonable range, it is necessary to make corresponding constraints on the power generation, supply and demand, energy storage and so on in the system.

(1) Balance between supply and demand

For the PV-B system, the total demand and supply need to be balanced at any moment.

$$D(t) = P_{PU}(t) + P_{BU}(t) + P_{GU}(t), \quad \forall\, t = 1, ..., T. \tag{3}$$

where, $D(t)$ represents the load demand of residential users at time t.

(2) Power operating constraints

The total photovoltaic capacity of a photovoltaic panels should be greater than or equal to the sum of the power supplied to the consumer, the battery and grid, taking into account the loss of power during transmission and conversion.

$$P_{PV}(t) \geq P_{PU}(t) + P_{PB}(t) + P_{PG}(t), \quad \forall\, t = 1, ..., T. \tag{4}$$

The upper limit of charge and discharge power of battery is not related to time, but only to the rated maximum power.

$$\begin{cases} P_{BU}(t) + P_{BG}(t) \leq P_{bat}^{rated}, & \forall\, t = 1, ..., T; \\ P_{PB}(t) + P_{GB}(t) \leq P_{bat}^{rated}, & \forall\, t = 1, ..., T; \end{cases} \tag{5}$$

Battery cannot be charged and discharged at the same time.

$$X_{ch}(t) + X_{dis}(t) \leq 1, \quad \forall t = 1, ..., T. \tag{6}$$

where, $X_{ch}(t)$ and $X_{dis}(t)$ denote respectively the charging and discharging state of battery at time t. $X_{ch}(t)$ =1 and $X_{dis}(t)$ =1 indicates that battery is in charge and discharge state at this time t.

In order to reduce the loss of battery and prolong their service life, the following constraint should be made on the state of charge of battery:

$$SoC^{\min} \leq SoC(t) \leq SoC^{\max}. \tag{7}$$

where, $SoC^{\max}$ and $SoC^{\min}$ represent the upper and lower limits of SoC of battery respectively.

(3) Charging and discharging constraint of battery from grid

The excess electricity will be stored in battery, when there is excess photovoltaic generation, and when the electricity price of grid is low or the photovoltaic generation is insufficient, electricity can also be purchased from grid. However, considering levelized cost of energy, it is necessary to make decisions about which time is suitable for battery to charge or discharge from grid. Therefore, the charge and discharge constraints of battery are shown below:

$$\rho\left(t_{dis}\right)-\rho\left(t_{ch}\right)\geq 2\cdot LCOS. \tag{8}$$

where, t_{ch} and t_{dis} represents the charge and discharge time of battery, respectively.

(4) Transmission constraints of photovoltaic generation

When the electricity flows from the photovoltaic panels to battery or grid, which indicates that the photovoltaic generation is in excess at this time. Therefore, it is necessary to prohibit the PV-B system from purchasing electricity from grid. When there is excess power generation of photovoltaic panels, in order to make the optimization result more accurate and reasonable, the following constraints are needed:

$$\left\{\begin{array}{l} P_{PB}\left(t\right)\cdot P_{GU}\left(t\right)=0,\ \forall t=1,...,T; \\ P_{PB}\left(t\right)\cdot P_{GB}\left(t\right)=0,\ \forall t=1,...,T; \\ P_{PG}\left(t\right)\cdot P_{GU}\left(t\right)=0,\ \forall t=1,...,T; \\ P_{PG}\left(t\right)\cdot P_{GB}\left(t\right)=0,\ \forall t=1,...,T; \end{array}\right. \tag{9}$$

4 Systems of power generation and energy storage

4.1 Photovoltaic panels

The photovoltaic generation is generally related to the rated power of the photovoltaic panels, rated working temperature, solar irradiance, environmental temperature, etc. Its output power is shown below [7][8]:

$$P_{PV}^{r}\left(t\right)=P_{PV,STC}\cdot N_{PV\mathrm{s}}\frac{I\left(t\right)}{1000}\left[1-\alpha\left(T_c-25\right)\right]\cdot\left(1-\vartheta\right)^{r}. \tag{10}$$

$$T_c{=}T_a+\frac{I\left(t\right)}{800}\left(NOCT-200\right). \tag{11}$$

where, $P_{PV}^{r}\left(t\right)$ represents the output power of photovoltaic panels at time t, r represents the years of working of photovoltaic panels;$P_{PV,STC}$ indicates the output power of photovoltaic panels under standard test conditions; $N_{PV\mathrm{s}}$ is the number of photovoltaic panels; $I\left(t\right)$ is the solar irradiance at time t; α represents the power temperature coefficient; ϑ indicates the attenuation coefficient of photovoltaic panels; T_c is the temperature of surface of panels; T_a is the environment temperature; $NOCT$ represents the rated operating temperature of panels.

In order to accurately measure the cost of photovoltaic generation, the calculation method of levelized cost of electricity (LCOE) is often used, which is as shown below [9]:

$$LCOE=\frac{\sum\limits_{r=1}^{n}\frac{annual\cos t_r}{(1+i)^r}+TI-\frac{R}{(1+i)^r}}{\sum\limits_{r=1}^{n}\frac{Er}{(1+i)^r}}. \tag{12}$$

where, $annual\cos t_r$ indicates annual operating expense; TI is the total project investment; R represents the residual value of project; Er is the total power generation in year r; i indicates fixed discount rate.

4.2 Energy storage battery

The state of charge of a battery can be simply understood as the ratio of battery's remaining charge to its rated capacity. The state of charge of battery at time t+1 can be calculated by:

$$SoC\left(t{+}1\right)=\left(1{-}\sigma\right)\cdot SoC\left(t\right)+\Delta t\cdot\frac{P_B(t)}{C_n}. \tag{13}$$

where, $SoC\,(t)$ represents the state of charge of battery at time t; $P_B(t)$ indicates the power of charge and discharge power of battery at time t; σ is the self-discharge rate; C_n represents the rated capacity of battery.

In addition, this section also considers the charge and discharge efficiency of battery. The charge and discharge power of battery at time t is expressed as:

$$P_B(t)=\eta_{ch}\cdot(P_{PB}(t)+P_{GB}(t))\cdot X_{ch}\,(t)-\frac{P_{BG}(t)+P_{BU}(t)}{\eta_{dis}}\cdot X_{dis}\,(t)\,. \tag{14}$$

where, η_{ch} and η_{dis} indicate the charge and discharge efficiency of a battery.

In order to accurately measure the energy storage cost of a battery, the levelized cost of storage is used:

$$LCOS=\frac{Price}{SoC_{\text{rated}}\times N_{ESS}\times Efficiency}. \tag{15}$$

where, $Price$ is the price of battery; $Efficiency$ is the efficiency of battery.

5 Data, simulation and analysis

5.1 Data and parameters of model

(1) Photovoltaic panels

The daily power consumption curve of a typical residential user adopted in this chapter is shown in Figure 2. According to the user's daily electricity consumption, a 6 kWi's photovoltaic generation system is constructed. The photovoltaic generation module consists of 18 solar photovoltaic panels with a rated capacity of 0.34 kWp. The price of a single panel is 554.2 yuan, the standard output voltage is 32.6 volts and the output current is 10.43 ampere. The comprehensive conversion efficiency of the module is 18.38 percent. In addition, other cost components of solar photovoltaic modules include: 7 kWi's photovoltaic inverter (2600 yuan); the distribution box (700 yuan); controller (200 yuan), and other equipment and installation costs (500 yuan).

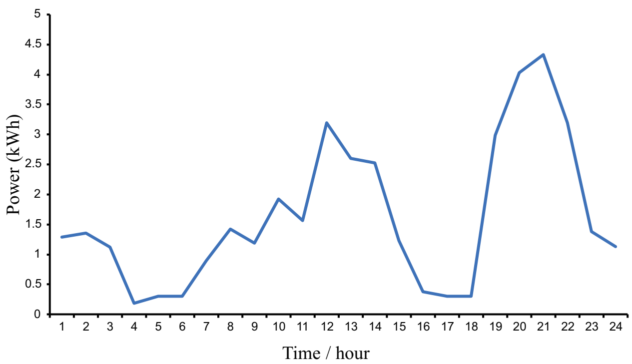

Figure 2: Daily electricity consumption curve of residential user

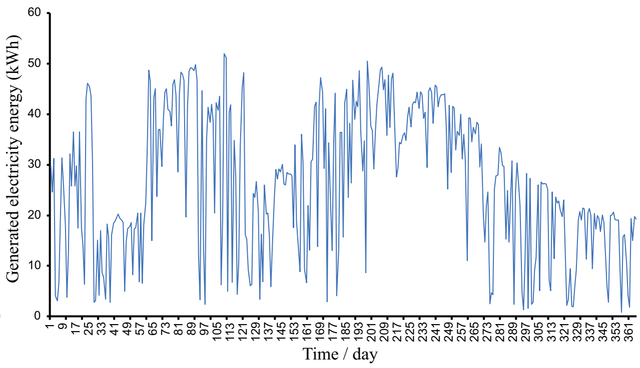

Figure 3: The daily output of solar panels

The daily power generation data is shown in Figure 3. According to the data, the total power generation of the 6 kwis photovoltaic generation system is about 9616 kWh in a year, and the average power generation is 26.36 kWh per day. Thus, it can be calculated by according to Equation (12) that $LCOE = 0.19$ yuan/kWh. And the annual operating cost is equivalent to 1 percent of the total investment of the system, the design life of photovoltaic modules is 15 years, and the fixed discount rate of the project is 8 percent. In addition, the attenuation coefficient of the photovoltaic module is 0.6 percent/ year, the power temperature coefficient is 0.0045, and the rated operating temperature of the solar panel is 46.

(2) Energy storage battery

According to the user's average daily electricity consumption (30 kWh) and the installed 6 $kW_i's$ photovoltaic generation system, the capacity of the energy storage system is designed to be 48 kWh, which is composed of 40 energy storage batteries, with a total cost of 20000 yuan. In order to reduce battery deterioration and prolong battery life, the discharge depth of battery is generally controlled within 20-80 percent. The discharge depth selected in this chapter is 55 percent, and the SoC range of battery is 40-95%. The battery has a design life of 10 years. Thus, according to Equation (15), the

LCOS can be calculated, which is 0.127 yuan/kWh. In addition, the maximum charging and discharging power of battery is 3 kW, the self-discharge rate of battery is 0.001, the charge and discharge efficiency is 90%.

5.2 Optimization method and framework

Framework of optimization of photovoltaic energy storage system is shown in Figure 4.

At time t, when the photovoltaic output power is greater than the load of residential users, the optimization decision is shown in the left half of Figure 4.

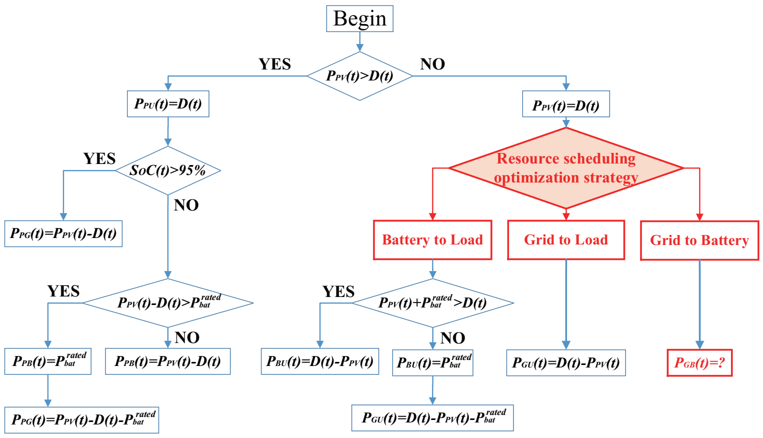

Figure 4: Framework of optimization of photovoltaic energy storage system

When the photovoltaic output power is less than the load demand of residential users, the problem of optimal scheduling of system resources by the optimization model will become more complex. According to the principle of priority load supply of photovoltaic generation, the power supplied by photovoltaic panels to residential users is equal to the photovoltaic output power at this time. For the part that photovoltaic generation fails to meet the load demand, it can be satisfied by discharging of battery and purchasing power from grid. And the function of the system optimization model to the resource scheduling optimization of PV-B system is reflected here. For battery, its charging and discharging state is affected by the real-time price, photovoltaic generation and load demand, etc. In addition, the current moment of decision not only affects residential users to charge and discharge to grid electricity purchasing cost, will also affect battery charged state, after which affect the charging and discharging of decision-making, namely the moment before charging and discharging power purchase behavior, and affects the battery charging and discharging of the next moment, and from grid electricity purchasing decisions, its corresponding cost of system changes. Therefore, how to minimize the cost of the system and maximize the utilization rate of the PV-B system by proposing reasonable decisions on charging and discharging and electricity purchase of the battery is the problem that the optimization model needs to solve.

5.3 Simulation results and analysis

In this section, the hourly observation data of solar irradiance of a photovoltaic power station in Gaoyou, Jiangsu province is used to carry out simulation analysis on the proposed optimization model and verify the effectiveness of the optimization scheduling of photovoltaic generation and energy storage system.

Figure 5 shows the photovoltaic generation and power distribution curves.When the photovoltaic generation is larger than the load demand of residential users (9:00-18:00), the photovoltaic panels will give priority to storing the surplus amount of photovoltaic generation after meeting the load demand of the users in battery. Secondly, if there is still surplus of photovoltaic generation, the photovoltaic panels will sell part of the surplus electricity to grid to exchange for profits.

Figure 6 shows the charging and discharging of battery in a day and the corresponding SoC curve. It can be seen that the initial value of SoC is 45%. After continuous charging, the SoC value of SoC reaches the maximum (70.81%) at 17:00, and after 6 hours of discharge, the SoC value of SoC drops to 40%. As can be seen from the figure, battery is mainly charged in two time periods: 4:00-6:00 and 9:00-17:00 respectively.The discharge time of the battery is mainly concentrated in 1:00 to 3:00, 7:00 to 8:00, and 19:00 to 24:00.

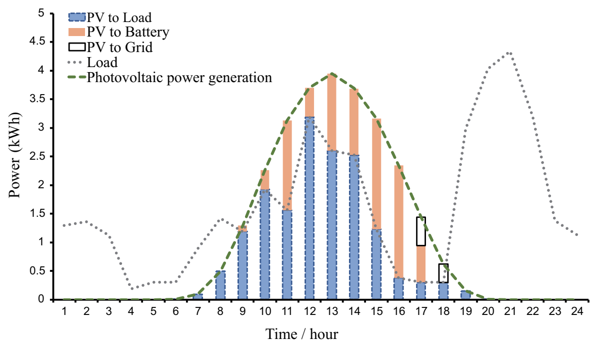

Figure 5: Solar power generation and power distribution

Figure 7 shows the household load and the composition of power supply.The power sources of residential users' load demand mainly include photovoltaic panels, battery and grid. From 1:00 to 6:00, the load demand of user is mainly supplied by battery and grid. When the electricity price of the power grid is too low from 4:00 to 6:00, the battery charges from the power grid at the highest charging power, so as to be used for load when the photovoltaic generation is insufficient or the electricity price is too high. From 4:00 to 6:00, when the electricity price is low, battery will be charged from grid at the highest charging power, and to be used for load when the photovoltaic generation is insufficient or the electricity price is too high. During the period from 7:00-8:00, the photovoltaic generation panels start to generate electricity, but the power is not enough to meet the load demand of residential users, so battery is used to supplement the remaining load demand of residential users. Between 20:00 and 24:00, battery cannot meet the needs of users, so grid is needed to supply power to residential users. In order to analyze the model optimization strategy, the role and effect

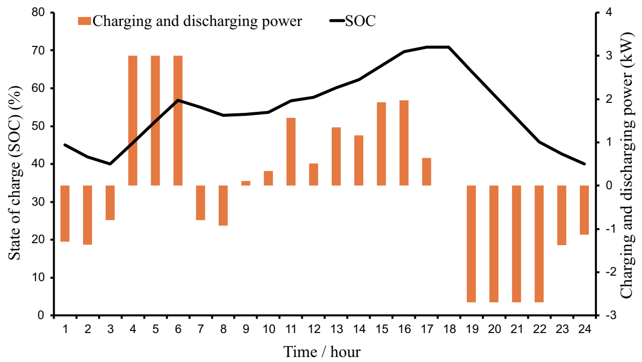

Figure 6: Charging and discharging power and SoC curve of energy storage system

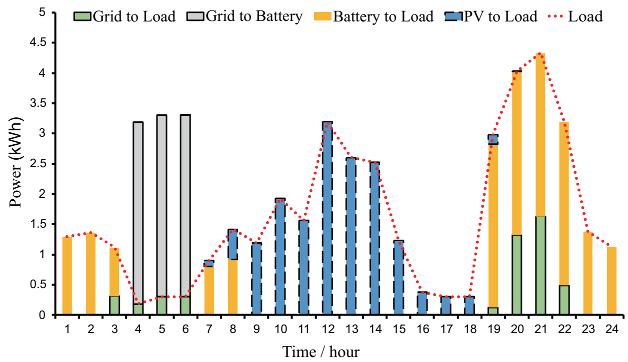

Figure 7: Household load and the composition of power supply

of constraint conditions in more detail from the optimization results, Figure 8 compares and analyzes five data including photovoltaic generation, electricity purchase from grid, charge and discharge of battery, load and price. First of all, in Equation (8), by considering the charge and discharge costs of battery, the time constraint between the electricity price and the charge and discharge of battery is established in this chapter. In the results presented in Figure 8, battery charging is concentrated at night and during the period of excessive photovoltaic generation in the daytime, and battery discharge is mainly at night with the high electricity price. Although the electricity price from 9:00 to 15:00 in the daytime also meets battery discharge conditions, the photovoltaic generation during this period is enough to meet the residential load, so there is no need to conduct battery discharge operation. In addition, the constraints of Equation (9) have shown that when the electricity flows from the photovoltaic generation panels to battery or grid, it is necessary to prohibit all electricity purchase behaviors of PV-B system from grid. This is well illustrated by the optimized result of 4:00-9:00 in Figure 8. The photovoltaic generation from 4:00 to 8:00 is less than the demand. At this time, there are three kinds of power dispatched to residential load, that is, charging and discharging of battery, grid and photovoltaic generation. With the increase of solar irradiation intensity, the power generation of solar photovoltaic at 9:00 can meet the demand of residential user. According to the requirements of constraints, it is necessary to forbid the PV-B system to purchase electricity from grid, so the charging of battery and power supply from grid to the load are all prohibited. In addition, the 9:00-18:00 time slot is also very good proof of this.

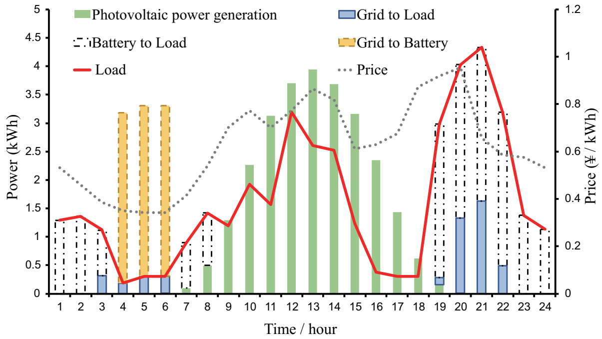

Figure 8: Schematic diagram of power flow in a micro-grid system

6 Conclusion

In this paper, a grid-connected distributed photovoltaic-battery micro-grid system for residential users is constructed. By considering the loss and charge and discharge costs of battery, a more reasonable optimal scheduling scheme is proposed. In addition, numerical simulation and case studies are carried out by using real solar radiation observation data. The research conclusions are therefore outlined as follows:

1) The photovoltaic-battery micro-grid system can significantly reduce the electricity cost of residential users, which has a certain promotion effect for the installation and popularization of small photovoltaic-battery micro-grid system in the residential field.

2) Compared with the system with only battery, the combined use of photovoltaic power generation and battery can effectively reduce the total amount of charge and discharge of the battery, thus reducing the loss of the battery in the process of use.

3) Compared with the micro-grid system lacking photovoltaic power generation or battery, the photovoltaic-battery micro-grid system has a higher utilization rate, and has higher independence and stability, as well as the ability to withstand severe weather and sudden grid emergencies.

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