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Optimization and Evaluation of PV-ESS Integrated Micro-grid Based on the Load

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Abstract: The micro-grid system combining with the energy intelligent management system provides a new idea for solving the new energy utilization. On the condition of time-of-use (TOU) price, this paper considers the multi-complementarity and constructs an integrated micro grid system based on load side, using photovoltaic (PV) and energy storage system (ESS) beside the electric supply. The paper also studies the on/off grid control of the micro grid, energy management and control of the storage, and analyses the economy and the promotional value of this system in combination of projects.

Keywords:PV-ESS;Microgrid;Energy management;Optimization

1 Introduction

The micro grid can improve the safety of power system and promote the access and the local consumption of renewable energy.In the future, the distributed micro grid based on renewable energy resources (wind and photovoltaic) will be the most effective way to solve the energy and environmental problems [1]. In order to ensure the safety and stability of the PV system and the power quality[2], it is necessary to supply with a certain amount of energy storage system [3],according to the user side load characteristic curve and the change of the PV power output. According to the given control strategy, the micro grid system will be stabilized and the output of PV will be consumed as much as possible.

The energy storage system can be charged at the valley power price, and the energy can be released at the peak power price to effectively suppress the power supply and reduce the power cost of the user[4]. With the development of technology, the cost of new energy will gradually decrease, and the economy of micro grid will be improved gradually. At home and abroad, there are many researches on the decision-making application of energy management[5, 6]. The existing researches mainly focus on the modeling and economic analysis of independent landscape storage system and family side optical storage system[7, 8],and[9] proposed a PV-battery based energy system model for community energy sharing. There are not many researches on the optimization analysis and evaluation of the distributed micro-grid system based on the actual demand of the actual industrial park users.

The contribution of this paper mainly includes: (1) We to provide a stable, reliable and economical multi-energy complementary energy supply solution for the demand side users of industrial enterprises and families. (2) This article combines the example of an industrial park in WuXi, China, the numerical simulation results show it has better efficiency and stability than the existing research method. (3) The results of this paper are in a comprehensive comparison with the real cases, which provides the basis for the optimal use of the optimal energy strategy at different times for different load users, and has practical feasibility.

2 Grid-connected photovoltaic storage integrated micro-grid

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The micro-grid system with PV and battery connected grid constructed in this paper is composed of distributed photovoltaic systems, energy storage systems, grid-connected power purchase/sales systems, and loads. The system implements three kinds of dispatching control measures: multi-power, multi-energy ratio, and bi-directional peaking.

The power of photovoltaic generation $P_{PV}(t)$ can be discribed by the following formula:

$$P_{PV}(t) = N \bullet P_r \bullet G(t) \bullet [1 + K \bullet ((T_{amb} + (0.0256 \times G(t))) - T_{ref})] / G_{ref} \tag{1}$$

where *N* is the number of photovoltaic panels, P_r represents the rated power of the photovoltaic panel under the standard conditions, $G(t)$ denotes the solar radiation at time *t*, and G_{ref} denotes the reference solar radiation under the standard conditions, *K* is the power temperature coefficient, T_{amb} is the ambient temperature, T_{ref} is the battery temperature.

Battery is the core of the energy storage system. The input power and output power, and charge and discharge status of battery should satisfy the following formula:

$$P_B(t) = [-P_{ch}(t) \bullet I_{ch}(t) \bullet f_{ch} + P_{dis}(t) \bullet I_{dis}(t)/f_{dis}] \bullet \Delta t \tag{2}$$

where $P_B(t)$ represents the quantity of the storage system charge or discharge at time *t*. $P_{ch}(t)$ and $P_{dis}(t)$ indicate the charge and discharge power of the battery at time*t*,respectively. f_{ch} and f_{dis} are the charge or discharge efficiency of the battery, respectively. $I_{ch}(t)$ and $I_{dis}(t)$ are 0-1 variables.

The power obtained from the main grid should satisfy the following formula:

$$P_E(t) = I_N(t) \bullet P_{GB}(t) - (1 - I_N(t)) \bullet P_{GS}(t)\,, \qquad t = 1, 2, \ldots, 24 \tag{3}$$

where $P_E(t)$ represents the power of the system to purchase electricity from the grid at time *t*, $P_{GB}(t)$ represents the power obtained from the main grid at time *t*. $P_{GS}(t)$ represents the power sold to the main grid at time *t*. $I_N(t)$ is 0-1 variables defined as follow:

$$I_N(t) = \begin{cases} 1, & purchase\ electricity, \\ 0, & others, \end{cases} \tag{4}$$

In this paper, the cost of power generation of micro-grid (referred to as the cost of power generation) and the interaction of the micro-grid and the traditional grid (referred to as interation power) as indicators of optimization of optical and storage grid-type micro-grid system configuration. The optimization objective function of total power generation cost is:

$$f_1 = \sum_{t=1}^{24} \left[P_{PV}(t) \times m + I_N(t) \times P_{GB}(t) \times g_{GB}(t) - (1 - I_N(t)) \times P_{GS}(t) \times g_{GS}(t)\right] + h \tag{5}$$

where *m* represents the cost of electricity generated by photovoltaic power generation, *h* is the fixed cost per unit time of the micro-grid, $g_{GB}(t)$ and $g_{GS}(t)$ are the prices of electricity purchased and sold by the system.

Second, while the economic benefits, we must also consider the stability of the system. The optimization function of the interactive electricity quantity is defined as:

$$f_2 = \sum_{t=1}^{24} I_N(t) \times P_{GB}(t) + (1 - I_N(t)) \times P_{GS}(t) \tag{6}$$

In this paper, a multi-objective nonlinear mixed-integer model is used to optimize the two aspects of the generation cost of the distributed generation side and the interaction power with the grid. The micro-grid needs to meet the following constraints during operation.

$$P_E(t) + P_{PV}(t) + P_B(t) = P_L(t)\,, \qquad t = 1, 2, \ldots, 24 \tag{7}$$

where $P_L(t)$ represents total load demand at time *t*.

$$E(t) = E_0 - \sum_{s=1}^{t} P_B(s)\,, \qquad t = 1, 2, \ldots, 24 \tag{8}$$

$$SOC_{min} \le E(t) \le SOC_{max}\,, \qquad t = 1, 2, \ldots, 24 \tag{9}$$

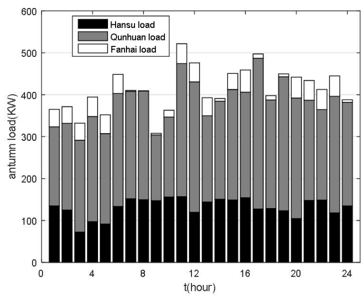

Figure 1: Typical daily load demand curves for three companies in Meicun Industrial Park in the autumn.

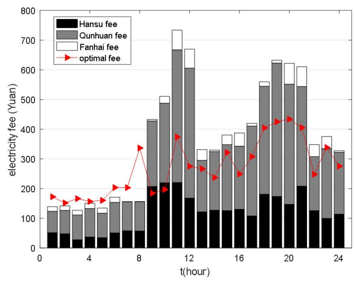

Figure 2: Typical daily electricity expenses curves for three companies in Meicun Industrial Park in the autumn.

wheree $E(t)$ is current power of storage equipment, and SOC_{min} and SOC_{max} represent the lowest and highest capacity of energy storage equipment respectively.

$$I_{ch}(t) + I_{dis}(t) \leq 1, \qquad t = 1, 2, \ldots, 24 \tag{10}$$

where $I_{ch}(t)$ and $I_{dis}(t)$ are 0-1 variables defined as follow:

$$I_{ch}(t) = \begin{cases} 1, & charge \\ 0, & others \end{cases}, \qquad t = 1, 2, \cdots, 24 \tag{11}$$

$$I_{dis}(t) = \begin{cases} 1, & discharge \\ 0, & others \end{cases}, \qquad t = 1, 2, \cdots, 24 \tag{12}$$

$$0 \leq P_{ch}(t) \leq P_{ch,max}, \qquad t = 1, 2, \ldots, 24 \tag{13}$$

$$0 \leq P_{dis}(t) \leq P_{dis,max}, \qquad t = 1, 2, \ldots, 24 \tag{14}$$

where $P_{ch}(t)$ and $P_{dis}(t)$ represents the charging and discharging power of the energy storage equipment respectively, $P_{ch,max}$ and $P_{dis,max}$represent the maximum power of the charging and discharging of energy storage equipment respectively.

3 Data

Meicun Micro-grid Project is located in Wuxi New District of Jiangsu Province. The project is funded by GCL-Poly Energy Holdings Limited.

The Meicun Micro-grid project serves three companies in the Meicun Industrial Park (Hansu, Qunhuan, and Fanhai). Fig.1 shows the typical daily load demand curves of these three companies in the autumn (September 1). Fig.2 shows the time-of-use expenses for the three companies on a typical day in the autumn, and most of the electricity peak period coincides with the peak of electricity price (see Fig.4).

The daily solar radiation horizontal data(unit in $KWh/m^2 \bullet day$) can be obtained from PVsyst. The solar power and the measured hourly solar radiation $G(t)$ (black dotted) and ambient temperature $T_{amb}(t)$ (red solid) in Wuxi is shown in Fig.3. In this project, TOU pricing are split into three time periods, and the peak-to-valley price ratio is *1.67:1:0.38* as shown in Fig.4. More details are presented in Table 1.

4 Numerical results analysis

The parameters in Fig.5-8 are chosen as:the weight of cost of power generation *w=0.5*, the initial charge of the battery $E_0 = 200KWh$, maximum number of photovoltaic panels *N=2000*, battery capacity cap $SOC_{max} = 10^6 Wh$.

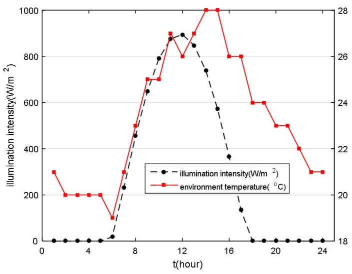

Figure 3: Illumination intensity and environment temperature curve on the autumn typical day in Wuxi.(data source: PVsyst)

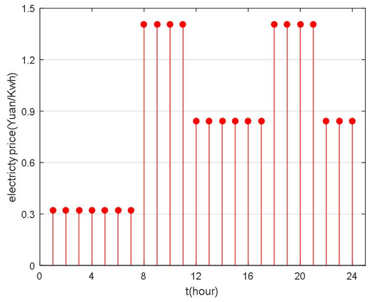

Figure 4: Electricity price in Wuxi industrial park.

Table 1: Related parameters.

Symbols	Meaning	Value(unit)
f_{ch}	Battery efficiency during charging	0.94
f_{dis}	Battery efficiency during discharging	0.94
G_{ref}	Solar radiation at standard condition	$1000W/m^2$
K	Temperature coefficient of the maximum power	$-0.0047\,(1/^{o}C)$
m	Cost per KWh of PV	$0.42Yuan$
P_r	Rate power of each PV panel	$260W$
$P_{ch,max}$	Maximum battery charging during each time interval	10^5W
$P_{dis,max}$	Maximum battery discharging during each time interval	10^5W
SOC_{min}	Minimum charge of the battery capacity	10^5W
T_{ref}	Ambient temperature	$25^{o}C$

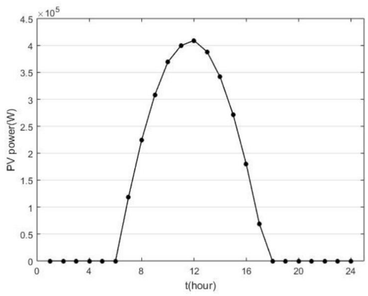

Figure 5: Photovoltaic power generation curve of TWD.

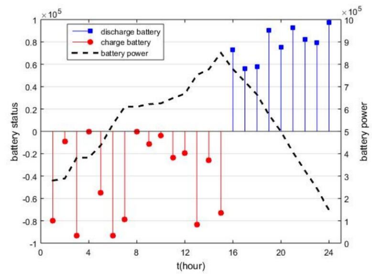

Figure 6: Battery capacity change curve of TAD.

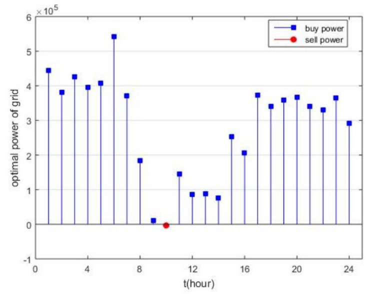

Figure 7: Power grid purchase/sale electricity curve of TAD.

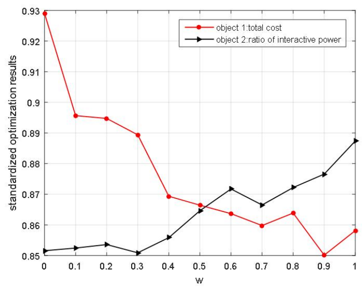

Figure 8: Objective function curves when *w* change of TAD.

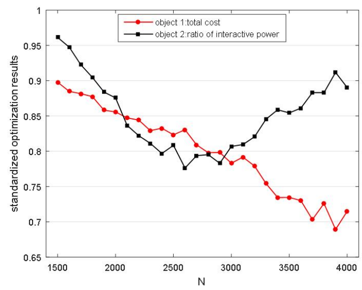

Figure 9: Objective function curves when *N* change of TAD.

According to the formula (1) and (2), the curve of PV power generation curve and battery capacity in the 24 hours of TAD is calculated, as shown in Fig.5 and 6. In Fig.6, from 0 o'clock to 7 o'clock, due to the low power grid, the system relies mainly on the power grid to charge the battery. At time 8-11, the power grid's electricity price is very high, the PV output is significantly increased (see Fig.5). The system mainly relies on PV power generation to charge the battery. At time 13-15, the users load (see Fig.1) decreased slightly, while the power price of the grid decreased, and the capacity of the battery increased significantly. The battery capacity reaches its maximum at time 15. After then, the battery capacity has decreased. And the battery discharge curve (at time 16-24) is mainly affected by users' load and grid electricity price (see Fig.4).

Fig.7 shows the purchase/sale electricity curve in 24 hours of TAD in power grid. During one day, only at 10 o'clock, the system will sell electricity to the grid (red dots), and other times will be purchased (blue dots). At 0-7, the grid electricity price is low, and the system adopts the strategy of buying more power, which is partly used to provide the load, and the other part is used for storage to achieve higher economic returns. At 8-16, the PV output is relatively high, and the cost of PV power is lower than the grid electricity price in this period, and the system purchases less power from the grid.

The optimized electricity cost comparison after optimization is shown in red line of Fig.2. The total electric charge is about *8846Yuan*, and the total electricity charge is *6493Yuan* after optimization, which is about reducing 27%. And when the electricity price is low at 0-7, the micro grid will buy electricity from the main power grid and store it, so the electricity bill is higher than before. At 8 o'clock, the electricity price is high. Although the battery is temporarily suspended, it still needs to buy electricity from the power grid to meet the demand of the users' load, so the electricity bill has a small peak. At 9-10, the users' load drops and the PV power increases, and the electricity bill drops significantly. At 11 o'clock, the users' load reaches the peak, the PV power increases, and the electricity bill increases significantly. At 12 o'clock, the users' load is reduced, the PV power reaches the peak, and the electricity price falls back. At 16 o'clock the battery began to discharge, and the purchase electricity was reduced. In the evening, the peak hours of the electricity bill coincide with the peak period of the electricity price, which is at 18-21.

At different stages of development, people have different requirements on the economy of micro grid and the stability of main grid. The two objective functions change with the weight *w* of f_1, see Fig.8.

The two objective functions change with the change of the number of PV panels limit *N*, as shown in Fig.11. Cost

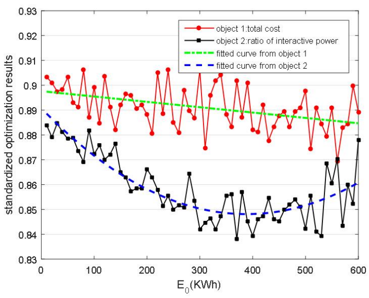

Figure 10: Objective function curves when E_0 change of TAD.

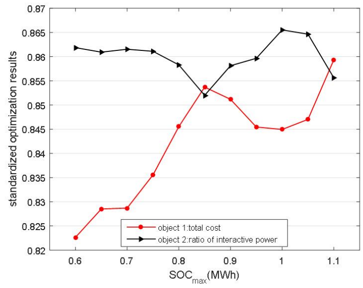

Figure 11: Objective function curves when SOC_{max} change of TAD.

optimization function values decrease with the increase of *N*, because the number of PV panels limit *N* increased will lead to the increasing of the cost of PV power generation. The value of the interaction power function decreases first and then increases with the change of *N*. The current parameter value is *N=2000*, and by optimization, the optimal value of *N=2800*.

The two objective functions change with the change of the initial battery power E_0, shown in Fig. 10. Power generation cost optimization function overall remain the trend of decrease with the increase of E_0. The value of the interaction power function decreases first and then increases with the change of E_0. The current parameter value is $E_0 = 200KWh$, which is best near $E_0 = 400KWh$. The two objective functions change with the change of the capacity of the battery limit SOC_{max}, see Fig. 11. Cost optimization function and interactive power optimization function as the change of SOC_{max} showed opposite change tendency. In terms of stability, when $SOC_{max} = 0.85MWh$, the interaction power is low and the stability is the best.

In order to make a comprehensive evaluation of the light energy storage and micro-grid system in different seasons, we studied the typical day of the light storage system in winter (December 15). There are some obvious changes in typical winter days compared with typical autumn days:(1)The winter user load is low and shows greater volatility.(2)Winter temperature and sunshine are significantly weaker than in autumn. PV power generation has dropped from *400KW* to *280KW*, and the amount of electricity produced during the day has also decreased significantly.(3)Insufficient utilization of battery in winter. Only 17 to 18 points per day are more than half the limit of the battery capacity. In winter, the battery discharged repeatedly between 0 and 17 points.(4)In winter, the electric purchasing curve fluctuates violently, and the purchase quantity decreases rapidly at night. Electrical behavior, in addition, different from the autumn is available only from the grid power purchase all winter time, significantly less than photovoltaic power. (5)After optimization in winter, the total electricity bill was *3822Yuan*,down about 23.5%.

5 Conclusions

In this paper, under the condition of time-sharing electricity price, the original single on the way of power supply can complement each other, in order to control costs and reduce the micro grid dependence, for the purpose of construct a light, integrated micro grid storage system based on load. In this paper, the optimization of grid control, energy management and battery control is studied, and the economic benefit and promotion value of the system are analyzed. With the instance of the China WuXi industrial park, user load data, light intensity and environment temperature data are derived from the actual, in view of the same user in different light and ambient temperatures of different load were analyzed. It is feasible and operable for micro grid users to adopt the optimal strategy at different times.

The shortcomings of this paper and further work in the future.(1)The future can be according to the different features of micro energy projects in the power grid research a variety of distributed new energy (wind, light,gas and other energy coordination coupling,effectively change the output of the wind power and photovoltaic,reduce the impact of volatility on the grid.(2)This article without fully considering the physical properties of the battery charge and discharge, battery charging and discharging efficiency and battery capacity upper and lower are simplified into a constant,in fact,its value is changing along with the using time and frequency.(3)The energy endowment of different regions, the use of different users and the environmental constraints of different regions are very different. In the future,we can study micro grids of different types and structures in different regions. The demand response research can be carried out for different user characteristics,and the mode of spontaneous self-use is discussed.(4)This paper studies the influence of different weights on the fitness of the system.Future for different micro grid users to carry out the investigation on of the project,in combination with experimental economics, from the user's electricity usage,psychological factors,such as multi-angle analysis of micro grid users at different times for the economy and stability of the micro grid focuses on considerations of the degree of rational quantification was carried on.(5)In the process of construction of off-grid micro-grid project,different forms of energy utilization need to be designed.Therefore,the interaction and restriction of existing mechanisms including power and gas are also worth paying attention to.

This paper provides a stable,reliable and economical multi-energy complementary energy supply solution for industrial enterprises and families.It is of great significance for the application demonstration and promotion of the optical and storage integrated grid-connected micro grid in the industrial park.

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