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Optimal Scheduling of Industrial Task-Continuous Load Management for Smart Power Utilization

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Abstract: In the context of climate change and energy crisis around the world, an increasing amount of attention has been paid to developing clean energy and improving energy efficiency. The penetration of distributed generation (DG) is increasing rapidly on the user's side of an increasingly intelligent power system. This paper proposes an optimization method for industrial task-continuous load management in which distributed generation (including photovoltaic systems and wind generation) and energy storage devices are both considered. To begin with, a model of distributed generation and an energy storage device are built. Then, subject to various constraints, an operation optimization problem is formulated to maximize user profit, renewable energy efficiency, and the local consumption of distributed generation. Finally, the effectiveness of the method is verified by comparing user profit under different power modes.

Keywords: demand response; distributed generation; smart power utilization; task-continuous load

1. Introduction

Faced with the increasingly severe circumstances of energy and the environment, many actions with respect to renewable energy have been taken around the world. One of the most important targets is to improve the access capacity of renewable energy on the user's side. With the development of smart grids and the implementation of related policies, many users have already attempted to use distributed energy. However, the asynchrony between the output of distributed generation and the users' loads leads to a low utilization rate of renewable energy and low profit for users. To make matters worse, the intermittence of renewable energy may lead to harmful effects on the distribution grid or even power failure due to the absence of a reasonable program [1]. Therefore, the local consumption of distributed generation is an important direction of energy management for both power grids and users. The users of electric power can be divided into residential users, utility users, commercial users, and industrial users. With the development of smart devices and advanced metering infrastructures, several programs of energy management for users have been proposed. The conception of user-side energy management has been proposed, including home energy management systems, building energy management systems, and enterprise energy management systems [2]. Based on user-side energy management systems, smart communities, smart industrial parks, and smart grids are steadily developing [3]. However, many existing energy management systems focus on energy monitoring systems rather than systems with optimization functions.

There is much literature about energy management and optimization. Among them, demand side management [4,5] and demand response technology are the main focus [6,7]. References [8–12] explore the method of improving energy efficiency with the assistance of demand response technology, aimed at water heaters, air conditioners, fridges, and washing machines. Reference [13] keeps the balance between economy and comfort by introducing comfort constraints in energy strategies that include distributed generation. In addition, the study of a micro-grid energy management system, analogous to the demand side energy management system, is also a hot topic for researchers [14]. As for the building energy management systems, in reference [15], a semi-centralized decision-making methodology using multi-agent systems was proposed to improve energy efficiency and reduce energy costs. Reference [16] introduces the actual experiment of using a building energy management system. After installing the building energy management system in a 21-floor building in Tirana, the total electrical energy footprint of the building was 135 kWh/m^2/year; it was 200 kWh/m^2/year before the installation of the system, which indeed is a massive drop. In addition, an enterprise energy management system was used in Guangzhou Iron and Steel Co., Ltd. (Guangzhou, China), to help them to arrange production [17].

However, there are still some issues that remain to be tackled. For one thing, the above existing studies, ignoring the distribution generation, cannot ensure the application of their technology to the demand-side energy management, which includes distributed generation. Moreover, the available research does not take the industrial task-continuous load into consideration when doing research on energy management. The main contribution of this paper lies in building a model of energy management considering the synchronization between the distributed generation and the industrial task-continuous load. In addition, this paper proposes a method that optimizes the industrial task-continuous load schedule to improve both the local consumption of the distributed generation and the economic benefit of users. Specifically, the contribution of this paper is as follows:

(1) The model of task-continuous load proposed in this paper is established, which can accurately describe the mathematical characteristic of the task-continuous load in the industry process.
(2) Regarding the states of industrial task-continuous load in time slots different from the controlled variables, the optimal solutions solved by this model of energy management can be directly applied to the industry process. That is to say, the method in this paper indeed has promising prospects of promotion in the industry.
(3) In addition, this paper shows that the model of energy management can shift the load to the period when the output of distributed generation is high and can shift the output power of the distributed generation into the battery. This results in a higher rate of self-occupied distributed generation, increasing the benefit for users.

2. The Model of Task-Continuous Load

Task-continuous load is a special kind of load that has been widely used in the industry process. Such kind of load is usually composed of several highly continuous devices. Each device is activated and works at different times, and the completion of the task requires the process flow containing all devices. Taking the process of the oxygen top blown converter, for instance, the processes that include making up raw material, adding molten iron, adding oxygen, and tapping are closely connected. In addition, the electricity consumption of each process is quite different from each other. Task-continuous load achieves cyclical fluctuation in terms of electricity consumption and often lasts for a long time, such as the loads of the production line and the iron metallurgy industry. The model of task-continuous load is established as follows.

It is assumed that k is the serial of the time slots, $k \in \{1, 2, 3, \ldots\ldots, T\}$, and $x_i(k)$ is the state of the ith device's switch at the kth time slot, where "1" refers to "on" while "0" refers to "off." P_i is the power rating of the ith process and $P_i(k)$ is the power of the ith process at the kth time slot. Therefore,

$$P_i(k) = P_i \times x_i(k) = \begin{cases} P_i & x_i(k) = 1 \\ 0 & x_i(k) = 0 \end{cases} \tag{1}$$

Task-continuous load should satisfy the following constraints.

2.1. The Constraint of On-Time

It is assumed that the on-time of the ith device is constrained by the working hours and process flow. That is to say, such a device must be turned off between the ath time slot and the bth time slot. Moreover, $k \in \{a, a+1, \ldots\ldots, b\} \subset \{1, 2, 3, \ldots\ldots, T\}$. This constraint is given by

$$\sum_{k=a}^{b} x_i(k) = 0 \tag{2}$$

2.2. The Constraint of Continuous Working

It is assumed that the ith device must work continuously from the cth time slot to the dth time slot. Moreover, $k \in \{c, c+1, \ldots\ldots, d\} \subset \{1, 2, 3, \ldots\ldots, T\}$. This constraint is given by

$$\prod_{k=c}^{d} x_i(k) = 1 \tag{3}$$

2.3. The Constraint of the Order of the Process Flow

It is assumed that, at the eth time slot, the ith procedure must be turned on, and the previous jth procedure must be accomplished. Moreover, $k \in \{1, 2, \ldots\ldots, e-1\} \subset \{1, 2, 3, \ldots\ldots, T\}$. If the jth procedure lasts for T_j time slots, this constraint is given by

$$x_i(k) \times \{\sum_{k=1}^{e-1} [x_j(k)/T_i] - 1\} = 0 \tag{4}$$

3. Model of Energy Optimization

User-side energy management, considering the type and significance of devices, provides a management scheme that makes optimal production plans to maximize users' benefits based on users' productive plans. Benefit maximization refers to the optimum of the property index such as time, cost, satisfaction, energy-saving, and emission reduction.

A typical user-side energy management system is shown in Figure 1. This system consists of a distributed generation unit, an energy storage unit, an inverter, a controller, and loads. In this system, electric supply is used to guarantee the normal operation of loads when the distributed generation unit fails to meet the demand.

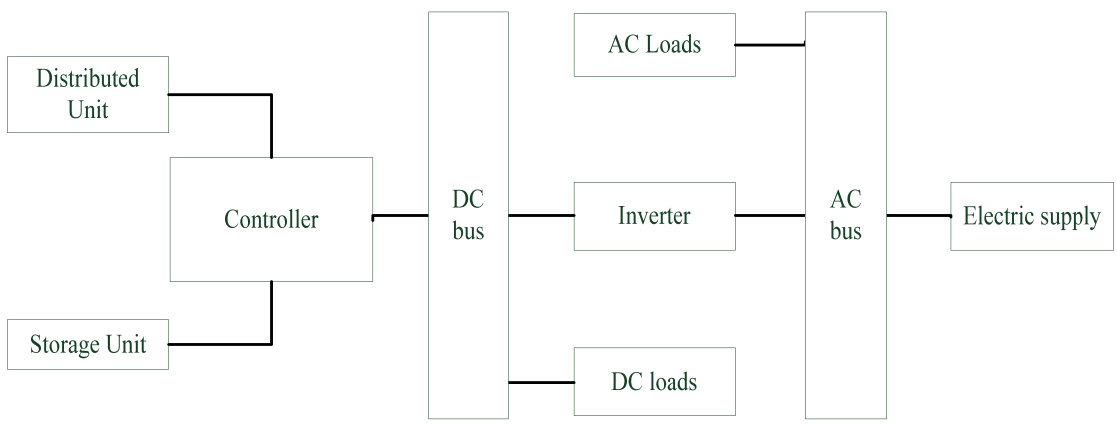

Figure 1. Structure of typical users' energy management system.

3.1. Maximum Revenue Target

For users with distributed generation units that are connected to the power grid, their economic benefit comes from two sources: (i) the subsidies for the local consumption of the distributed generation; and (ii) the money earned by selling redundant DG power to the power grid. In order to recover the cost of distributed generation equipment in the shortest time, the maximum revenue objective function ought to be adopted.

The maximum revenue target is shown as Equation (5):

$$\begin{aligned} \max F = & \sum_{k=1}^{T} C_{PV} P_{PV}(k) x_{PV}(k) \Delta t + \sum_{k=1}^{T} C_{Wind} P_{Wind}(k) x_{Wind}(k) \Delta t \\ & - \sum_{k=1}^{T} C_B P_B(k) \Delta t - \sum_{k=1}^{T} C_G(k) P_G(k) \Delta t \end{aligned} . \quad (5)$$

In Equation (5), the production planning cycle (usually be one day) is divided into T time slots, and each time slot lasts for Δt (usually one hour). In addition, the optimal strategy is allowed to execute at the initial moment of the kth time slot. The first part of users' revenue comes from the distributed generation (including the PV system and wind generation). Among the first part of the revenue, $x_{PV}(k)$ and $x_{Wind}(k)$ are the states of PV generation and wind generation, respectively, the controlled variables of the PV system and wind generation, where "1" refers to "on" and "0" refers to "off." $P_{PV}(k)$ and $P_{Wind}(k)$ represent the active power of PV generation and wind generation. At the same time, C_{PV} and C_{Wind} are the PV system's and wind generation's subsidized price of self-occupation, and usually are the same value. The second component of the objective is the revenue from the storage battery. Comparing with the distributed generation, the battery is allowed to charge or discharge. Therefore, the active power of the storage battery $P_B(k)$ can be negative. When $P_B(k) > 0$, the storage battery discharges, and, when $P_B(k) < 0$, the storage battery charges. Moreover, C_B is the generating cost of the storage battery. At last, the third part of the revenue comes from buying or selling the residuary power to the grid. Correspondingly, $P_G(k)$ represents the active power of the electric supply. When $P_G(k) < 0$, the distributed generation offers the electric energy back, and $C_G(k)$ is the difference between the acquisition price of DG and DG subsidized price of self-occupied at the kth time slot. However, when $P_G(k) > 0$, $C_G(k)$ is the electricity price of the initial moment of the kth time slot.

3.2. Active Power Balance Constraint

Active power balance constraint is shown as Equation (6):

$$\sum P_L(k) = P_{ucl}(k) + \sum_{i=1}^{N} P_i(k) x_i(k) = P_{DG}(k) + P_B(k) + P_G(k) \quad (6)$$

$$P_{DG}(k) = P_{PV}(k) x_{PV}(k) + P_{Wind}(k) x_{Wind}(k) \quad (7)$$

In Equation (6), N is the total number of task-continuous load. $P_i(k)$ is the active power of the ith task-continuous device at the kth time slot, and $x_i(k)$ is the state of the switch at the kth time slot, where "1" refers to "on" and "0" refers to "off." $P_{ucl}(k)$ represents the active power of other uncontrollable loads at the kth time slot. Therefore, $\sum P_L(k)$ is the whole power consumption at the kth time slot. In Equation (7), $P_{DG}(k)$ is total output of the distributed generation, which is directly supplied to the users' energy management system.

3.3. Storage Battery Constraint

Storage battery constraint is shown as Equations (8)–(10):

$$\begin{aligned} P_B(k) &> -P_{B,c\max} \\ P_B(k) &< P_{B,d\max} \end{aligned} \quad (8)$$

$$SOC_{\min} < SOC(k) < SOC_{\max} \quad (9)$$

$$|SOC(1) - SOC(n)| < \delta \quad (10)$$

$P_{B,c\max}$ is the maximum charge power of the storage battery, and $P_{B,d\max}$ is the maximum discharge power of the storage battery. $SOC_{\max}$ and $SOC_{\min}$ are the superior limit and the inferior limit of the storage battery, respectively. $SOC_{\max}$ and $SOC_{\min}$ usually take 80% and 20%, respectively. $SOC(1)$ and $SOC(n)$ are the states of the battery at the start time and the terminal time. δ is usually 5%.

3.4. Transferable Load Contraint

To guarantee the production flow on the rails, the ability of the transferable task -continuous load ought to meet the demand of various kinds of production task constraints, such as the on-time constraint. The detailed computation is the same as Equations (1)–(4).

4. Model Solution

The model of energy management is like a knapsack problem: the independent variables are all integers, and the values of most independent variables are 0 or 1. The switch state of each load and the distributed generation is a question of whether a certain thing should be put into the bag or not. The constraints are analogous to the fact that the total weight of goods ought to be less than the capacity of the bag. The objective function is to maximize the total value of the goods in the bag. The whole model is to optimize the goods, and there is a total of 2^n solutions, where n is the number of the goods. Because the problem is linear, the dimension of the problem depends on the length of the schedulable period and the task of the schedulable load.

Therefore, in this paper, these switch states of each load and distributed generation are the controlled variables. The constraints of Equations (2)–(4) and (6)–(10) limit the feasible region of the controlled variables.

When the controlled variables of each solution are ascertained, the power of the task-continuous load, the distributed generation can be gained directly. While the power of the battery and grid should be calculated based on following the power supply flowchart, whose calculating process is shown in Figure 2. Firstly, the predicted power of the distributed generation $P_{DG}(k)$ and the total predicted power of the system $\sum P_L(k)$ should be calculated and compared so that further power flow between the users and the system can be ascertained. It is assumed that the power of the distributed generation and the total power of the system has been predicted. The method to account for inaccurate predictions is not discussed in this paper. Skipping to the second layer of the logic judgment, the state of the battery represented by its current $SOC(k)$ should be calculated. Finally, an economic scheduling assignment is provided based on (i) the state of the battery and the grid and (ii) the difference between the battery discharging cost and the price of the electric supply.

It is well known that a knapsack problem needs to be solved through iterative methods such as the branch and bound method, the dynamic planning method, and different kinds of intelligent algorithms. Generally, the PSO (Particle Swarm Optimization) algorithm, as one kind of intelligent optimization technique, has good performance in global optimization. Further, due to its simple structure, no need for gradient information of constraints, and few parameters in the algorithm, the PSO algorithm achieve suitable solutions in continuous and discrete optimization problems. Therefore, based on these features, the PSO algorithm is selected as the optimal method for solving.

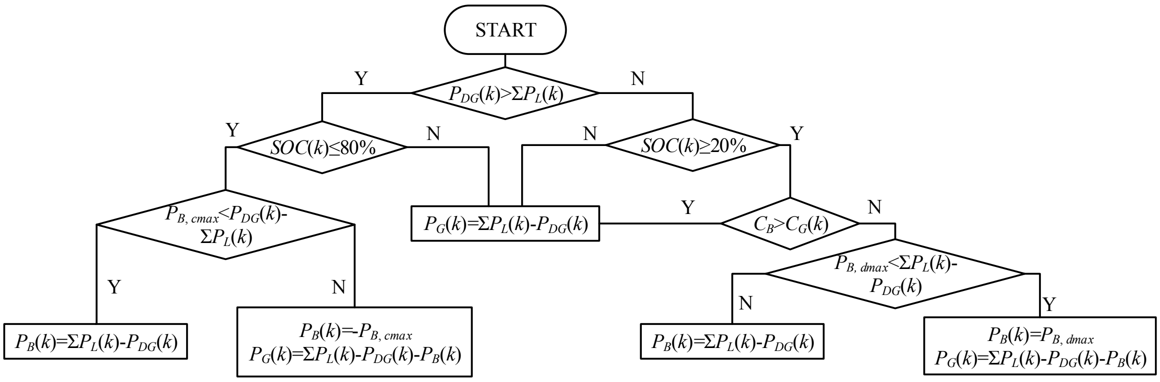

Figure 2. Flowchart of the power-supply-state judgment.

The PSO algorithm was firstly proposed by Kennedy and Eberhart [18]. This algorithm is a kind of stochastic evolutionary optimization method based on simulating bird population searches, that have good global search capacity. The basic theory of a PSO algorithm is briefly introduced as follows.

In the PSO algorithm, it is assumed that y_i and v_i are the position (the set of the controlled variables in this paper) and velocity (the evolutionary direction of the controlled variables) of the *i*th particle, while y_{i+1} and v_{i+1} represent the position and velocity of the next iteration. There are some parameters in the algorithm. For example, w is the inertia weight factor parameter in this algorithm, c_1 and c_2 are positive learning factor parameters, and r_1 and r_2 are random numbers between 0 and 1 and obey uniform distribution. Therefore, the position and velocity of the next iteration can be calculated by Equations (11) and (12):

$$v_j(i+1) = c_1 r_1 [y_{l,j} - y_j(i)] + c_2 r_2 [y_{g,j} - y_j(i)] + w v_j(i) \tag{11}$$

$$y_j(i+1) = y_j(i) + v_j(i+1). \tag{12}$$

If the position of a particle does not satisfy the constraints, the PSO algorithm should be modified and its velocity can be calculated by Equation (13):

$$v_j(i+1) = c_1 r_1 [y_{l,j} - y_j(i)] + c_2 r_2 [y_{g,j} - y_j(i)]. \tag{13}$$

In the process of the optimization of the modified PSO, the positions represent the states of the switch of each device in an industry process, and the velocities represent the changes in positions after each iteration [19].

The detailed optimization process of the PSO algorithm is shown in Figure 3. Firstly, the prediction of the load and distributed generation should be input into the algorithm. Then, the initial values of states of task-continuous load, PV generation, and wind generation (controlled variables) are obtained by randomly selecting in the set $\{0, 1\}$. After attaining the initial values, it is easy to gain the power of the battery and grid though the power supply approach provided by Figure 2. Hence, the value of the objective function can be calculated by Equation (5).

Further, the PSO method is utilized to iterate by itself to generate a more optimal solution. Moreover, in every iteration, the constraints are requested to be checked. The iterative Equation (11) is replaced by Equation (13) when the constraints are not satisfied. After attaining a new solution, the algorithm goes back to the process of calculating the power of the battery and the grid. Moreover, the stop criterion of the PSO algorithm is whether the number of iterations reaches the setting value.

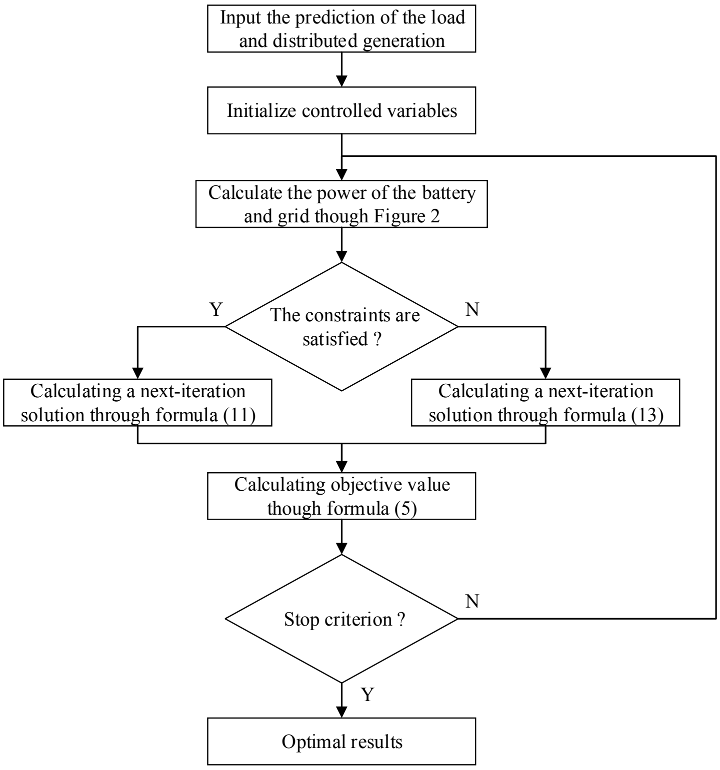

Figure 3. Flowchart of the PSO process.

5. Example Analysis

To simplify the model, the efficiency of the battery is regarded as 1. An example of industrial production processes in manufacturing devices is selected. It is assumed that this task includes 6 steps. In the production processes, Step 1 to Step 3 ought to be accomplished by order and Step 4 to Step 6 ought to be accomplished by order. That means before Step 2 starts, Step 1 should be accomplished already. Before Step 3 starts, Step 1 and Step 2 ought to be finished. Step 4, Step 5, and Step 6 are alike. The normal production work is divided into 24 time slots (each slot lasts for 1 h) and all the work ought to be carried out between 8:00 and 18:00.

As is shown in Figure 4, industrial electricity tariff is in accordance with city industrial production patterns, including three sections: peak, valley, and plain. In Figure 4, the unit is ¥. It represents RMB Yuan. The distributed unit is made up of a 600 kW PV system and a 300 kW wind-power generating unit. A 2000 Ah/480 V lead-acid storage battery is equipped in this system also. The life loss of the system is limited to 1/1000.

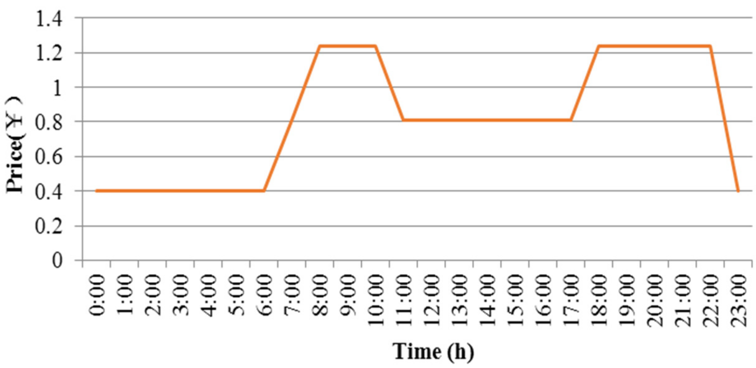

Figure 4. The price of electricity of a city.

Production time of the original, the original loads and the output of the distributed power are shown in Figure 5. The original loads consist of task-continuous processes and uncontrollable load, which is shown by the bars. Specifically, the load bars are stacked in a time slot. Therefore, the original maximum load power (800 kW) also occurs in the tariff peak.

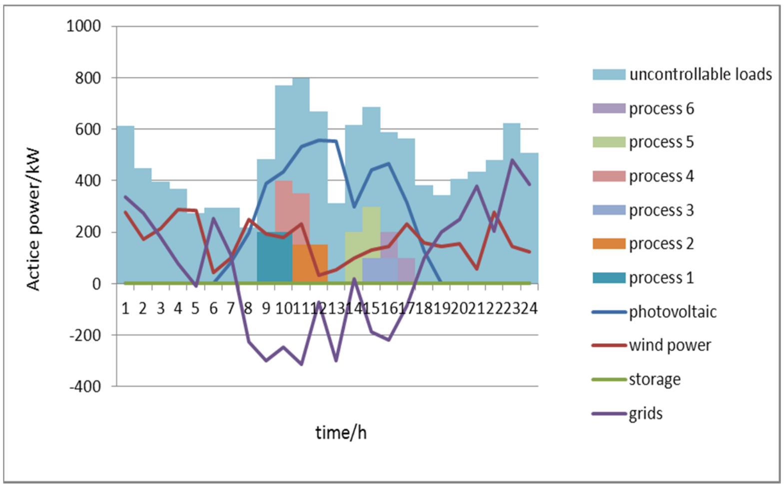

Figure 5. The stacked bars of the original loads and power curve of the distributed generation.

According to the energy management model proposed in this paper, the optimized power curve of the energy storage device and the optimal process order are shown in Figure 6. Comparing Figure 6 with Figure 4, it can be found that the period between 14:00 and 17:00 is the advantageous period where the electricity price is low and the output of PV maintains a high level. Therefore, Processes 1, 2, 4 and 5 are shifted into this period. Because of the characteristic of the task-continuous load, Processes 3 and 6 are shifted behind. At the same time, the results arrange the energy storage device to discharge to support Processes 3 and 6. The curve of grid in Figure 6 demonstrates that the schedule reduces both the selling power and the buying power in this period. The reduction of selling power benefits the local consumption of the distributed generation and the reduction of buying power is in favor of saving users' bills.

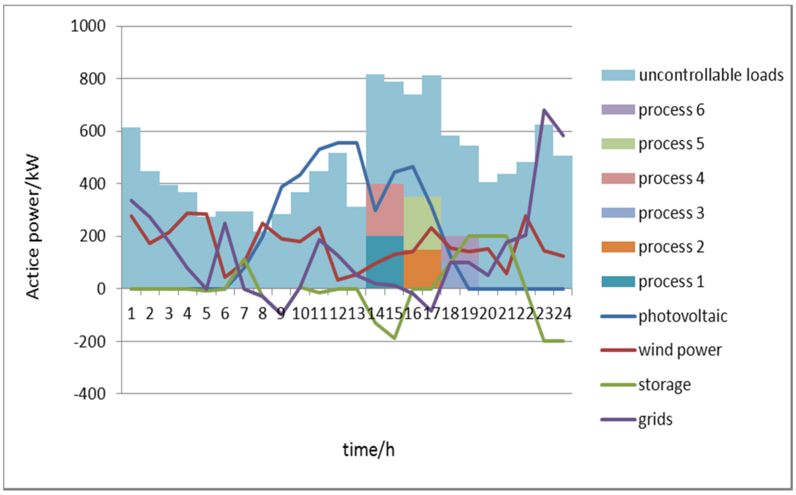

Figure 6. The process order and the power curve of the energy storage device after optimization.

Before optimization, the user's revenue is 6.53 Yuan. However, after optimization, the user's revenue is 8.57 Yuan. Therefore, the amount of revenue increase is 2.04 Yuan.

A comparison of production processes and power allocation sequences before and after optimization shows that this model reduces the load during the high tariff period time and transfers the load to the time slots when distributed energy generation is more prominent. From the power exchange with the grid and the actual power of the battery, we can verify that this model improves the local consumption of the distributed generation. On the other hand, the stability of the power grid has been improved with less distributed energy sent back to the grid. At the same time, the model improves the power curve and effectively responds to the electric tariff signal.

Specially, it is obvious that the former disordered working scheme of the task-continuous load is well reorganized and shifted. The optimal scheme of the task-continuous load shown in Figure 6 not only reduces the electricity bill but also makes the working process more compact and smooth. Due to the limitations of the time slot division and the user working time, the task-continuous load optimization becomes relatively concentrated. However, such planning has not uplifted peak loads, thus causing no extra pressure on the power grid. The result demonstrates the availability and efficiency of the energy management model proposed in this paper, which could be suitable for utilization in the industry.

6. Conclusions

Based on the task-continuous load characteristics, combined with the increasing integration of distributed generation, this paper presents a comprehensive consideration of distributed generation, energy storage charging/discharging, and task-continuous management strategies to optimize load operation. Compared to non-optimized energy management, the proposed strategy takes advantage of local distributed energy, improves the local consumption proportion of renewable energy sources, and improves the economic efficiency of users.

For user-side energy management issues, the toughest problem is not to obtain an optimal load schedule, but to accurately perceive and access users' needs. Therefore, future work will focus on how to analyze the influence of large amounts of load on the energy management system, how to improve optimization results, and how to realize a flexible and interactive smart power utilization in the environment of the smart grid.

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Conflicts of Interest: The authors declare no conflicts of interest.

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