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Research Article

Orderly Discharging Strategy for Electric Vehicles at Workplace Based on Time-of-Use Price

Lixing Chen[1] and Hong Zhang[2]

[1] *School of Electrical Engineering, Southeast University, Nanjing 210096, China*
[2] *School of Electrical and Information Engineering, Jiangsu University of Technology, Changzhou 213001, China*

Correspondence should be addressed to Lixing Chen; lixingchen19851210@163.com

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According to the parking features of electric vehicles (EVs) and load of production unit, a power supply system including EVs charging station was established, and an orderly discharging strategy for EVs was proposed as well to reduce the basic tariff of producer and improve the total benefits of EV discharging. Based on the target of maximizing the annual income of producer, considering the total benefits of EV discharging, the electric vehicle aggregator (EVA) and time-of-use (TOU) price were introduced to establish the optimization scheduling model of EVs discharging. Furthermore, an improved artificial fish swarm algorithm (IAFSA) combined with the penalty function methods was applied to solve the model. It can be shown from the simulation results that the optimal solution obtained by IAFSA is regarded as the orderly discharging strategy for EVs, which could reduce the basic tariff of producer and improve the total benefits of EV discharging.

1. Introduction

At present, there are two ways of pricing in China, namely, the single-part tariff and the two-part tariff. The two-part tariff, which is the big-industry price, includes basic electricity price and the electricity degree electricity price. The basic tariff related to two-part tariff can be calculated according to transformer capacity or maximum demand for user [1]. Most of production units usually pay the basic tariff according to the estimated maximum demand. Therefore, the basic tariff of the user who is large and medium-sized production unit is very expensive (e.g., when the maximum demand for a food manufacturer is 4.6 MW and its basic electricity price is 40.5 [Yuan/(kW·month)], the annual basic tariff is 2,235,600 Yuan [2]). Battery energy storage system (BESS), which can be used for load shifting to reduce the maximum demand, is a good way to reduce the basic tariff [3]. However, the cost of BESS is more expensive (e.g., if the best power of BESS is 1.52 MW and its capacity is 12.68 MWh, then its cost of investment is about 1,582,400 Yuan [3]), which is also a big cost for a production unit. If only it could find a battery replacement then the production unit will reduce its cost of investment.

With large-scale popularization of EVs, a large number of EVs, which can act as the battery replacements, will be parked at the workplace during working hours. The power consumption for an EV is low due to the short mileage between home and office [4]. Therefore, Producers can take advantage of sufficient discharging power of EVs to reduce their maximum demand and basic tariff. Furthermore, according to characteristics of EV users who respond to the TOU [5], EVs can be fully charged during valley price periods in residential areas [6, 7] and discharged in peak price time at the production units. So EV users can acquire profit from the price difference.

Based on TOU electricity price, this paper selects the discharging power of EVA in work time as the optimization variable and an optimization scheduling model of EVs discharging is established as well, which not only selects the target of maximizing the annual income of a producer to reduce the maximum demand and basic tariff but also considers EV user's profit from discharging. Then an improved artificial fish swarm algorithm (IAFSA) combined with the penalty

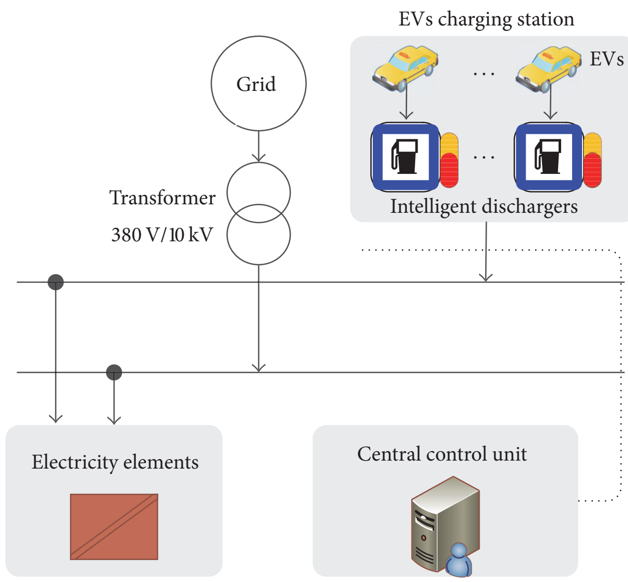

FIGURE 1: Power supply system including EVs charging station.

function methods can be applied to solve the model. Finally, the results of simulations show that the obtained orderly discharging strategy is effective and reliable.

2. Optimization Scheduling Model of EVs Discharging

2.1. Power Supply System Including Charging Station at Parking Lot. The researched power supply system including EVs charging station in this paper is comprised of a power grid, a distribution transformer, conventional electricity elements (i.e., electrical equipment of production), a central control unit (which is computer), and EVs charging station at parking lot (including EVs and intelligent dischargers); the system structure is as shown in Figure 1.

During the whole optimization period, the electricity demands of conventional electricity elements are satisfied by the power grid and EVs charging station. In particular, it is the assumption that the conventional electricity elements should use the power of EVs discharging in preference. Furthermore, it will not consider the situation when EVs charging station can supply the discharging power to power grid.

2.2. Discharging Capacity Model of EVA. When the EVA is not introduced, the total discharging capacity of EVs at time t can be represented as

$$\begin{aligned} Q_{\text{ev}}^{z}(t) &= \Delta Q_{\text{ev}}^{1}(t) + \cdots + \Delta Q_{\text{ev}}^{m}(t) \\ &= \int_{t_0}^{t} P_{\text{ev}}^{1}(t)\,\mathrm{d}t + \cdots + \int_{t_0}^{t} P_{\text{ev}}^{m}(t)\,\mathrm{d}t, \end{aligned} \tag{1}$$

where $\Delta Q_{\text{ev}}^{1}, \ldots, \Delta Q_{\text{ev}}^{m}$ are the discharging demands of EVs; $P_{\text{ev}}^{1}, \ldots, P_{\text{ev}}^{m}$ are the discharging power of EVs; m is the EV number; and t_0 is the starting time of the whole optimization period.

If a large number of EVs are modeled one by one, this will bound to increase the difficulty of modeling. If only these EVs could be regarded as an aggregator then it is feasibly and easily modeled. In order to establish the discharging capacity of EVA modeling, this paper takes the following assumptions into account:

(i) A general discharging way of EVs is selected to solve the issue that there are different discharging characteristics among EVs (set the discharging power range to [1, 10] (kW) [8]).

(ii) Parking hours for EVs are unified (the working hours of EV users are 8:00–18:00, which is relatively fixed at a production unit running on one shift).

(iii) Discharging behaviors of EVs are unified (EVs can discharge or stop at the same time, which is easily and uniformly controlled by intelligent dischargers and central control unit. In addition, the TOU for users in China is fixed for a relatively long time, which means that discharging periods of EVA can be decided in advance [9]).

Based on the above assumptions, if all of the EVs have the same discharging time, then a conversion factor can be introduced to guarantee the consistency of discharging progress among EVs and reflects each EV's individual contribution to the EVA. Therefore, the discharging power of EV i at time t can be expressed as

$$P_{\text{ev}}^{i}(t) = k_{\text{ev}}^{i} P_{\text{eva}}^{t}, \quad k_{\text{ev}}^{i} = \frac{\Delta Q_{\text{ev}}^{i}}{\sum_{i=1}^{m} \Delta Q_{\text{ev}}^{i}}, \tag{2}$$

where k_{ev}^{i} is a conversion factor (it can be calculated in advance according to discharging demands of EVs); P_{eva}^{t} is a discharging power of EVA at time t (it is the optimization variable of this paper).

According to formula (2), the central control unit can take control of each EV with orderly discharging. Thus, formula (1) can be discretized and resolved as follows:

$$\Delta Q_{\text{eva}}^{t} = \left(k_{\text{ev}}^{1} + \cdots + k_{\text{ev}}^{m}\right) \sum_{t=1}^{t} P_{\text{eva}}^{t} = \sum_{t=1}^{t} P_{\text{eva}}^{t}, \tag{3}$$

where $\Delta Q_{\text{eva}}^{t}$ is the total discharging capacity of EVA at time t.

Similar to an EV, the SOC of EVA at time t $\text{SOC}_{\text{eva}}^{t}$ can be described by a few factors including its battery capacity Q_{eva}, starting state of charge SSOC_{eva}, and the total discharging capacity of EVA at time t $\Delta Q_{\text{eva}}^{t}$.

$$\text{SOC}_{\text{eva}}^{t} = \text{SSOC}_{\text{eva}} - \frac{\Delta Q_{\text{eva}}^{t}}{Q_{\text{eva}}}, \tag{4}$$

where these factors can be represented as

$$\begin{aligned} \text{SSOC}_{\text{eva}} &= \frac{1}{\text{BC}_{\text{eva}}} \sum_{i=1}^{m} \text{SSOC}_{\text{ev}}^{i} Q_{\text{ev}}^{i}, \\ Q_{\text{eva}} &= \sum_{i=1}^{m} Q_{\text{ev}}^{i}, \end{aligned} \tag{5}$$

where $\mathrm{SSOC}_{\mathrm{ev}}^{i}$ is the starting state of charge of EV i and Q_{ev}^{i} is the battery capacity of EV i.

2.3. Multiobjective Functions

2.3.1. Annual Earnings for EVs Charging Station. Most of the production units usually pay the basic tariff based on the maximum demand which can be estimated. EVs mounted at the low voltage side of distribution system can be used for load shifting to reduce the maximum demand and the basic tariff of a production unit. Thus, the annual earnings without the cost of EVs charging station investment can be expressed as

$$\begin{gathered} C_1 = 12e_{\gamma}\left(P_{\mathrm{st}}^{\max} - P_e^{\max}\right), \\ P_e^t = P_{\mathrm{st}}^t - \eta_d P_{\mathrm{eva}}^t, \quad t = 1,\ldots,n, \end{gathered} \tag{6}$$

where $P_{\mathrm{st}}^{\max}$ is the maximum conventional load (kW); e_{γ} is basic electricity price [Yuan/(kW·month)]; $P_e^{\max}$ is the maximum equivalent load (kW); P_e^t is equivalent load (kW) at time t; P_{st}^t is conventional load (kW) at time t; η_d is discharging efficiency of EVA; P_{eva}^t is discharging power of EVA (kW) at time t; and n is the divided number of the whole optimization period.

The cost of EVs charging station investment mainly includes the cost of EV discharging device and operation and maintenance instead of the expensive batteries, which can be expressed as

$$C_2 = m\left(k_w C_w + C_m\right), \tag{7}$$

where k_w is fixed depreciation rate of the discharging device; C_w is cost per discharger; and C_m is annual cost of operation and maintenance per discharger.

Based on formulae (6) and (7), the objective function of annual earnings for EVs charging station can be expressed as

$$\max \quad F_1\left(P_{\mathrm{eva}}^w\right) = \max\left(C_1 - C_2\right). \tag{8}$$

2.3.2. Annual Discharging Earnings for EVs. According to characteristics of EV users who respond to the TOU, EVs can be fully charged during valley price periods in residential areas and discharged in peak price time at the production units. Therefore, the annual acquired profit from the price difference for EV users can be expressed as

$$\max \quad F_2\left(P_{\mathrm{eva}}^w\right) = \max\left[\mu\sum_{t=1}^{n}\left(e_t - e_0\right)P_{\mathrm{eva}}^t\right], \tag{9}$$

where μ is the devoted times for EV charging station in a year (it is set to 330); e_t is discharging price of EVs, which is peak price at production units; and e_0 is charging price of EVs, which is valley price in residential areas.

2.4. Constraints. (1) Considering the capability of output power for a discharger, the maximum discharging power of EVs at each period is less than the maximum output power of a discharger. According to formula (1), the discharging power of EVA is constrained by the following:

$$P_{\mathrm{eva}}^t \le \frac{P_r^{\max}}{\max\left(k_{\mathrm{ev}}^i\right)}, \quad t = 1,\ldots,n, \tag{10}$$

where $P_r^{\max}$ is maximum power of discharger.

(2) The situation when EVs charging station can supply discharging power to power grid is not considered. Thus, the discharging power for EVA is less than the load of conventional electricity elements.

$$P_{\mathrm{eva}}^t \le P_{\mathrm{st}}^t, \quad t = 1,\ldots,n. \tag{11}$$

(3) Considering the discharging capability of EVA battery, the total discharging energy of EVA is less than the maximum discharging demand of EVA.

$$\sum_{t=1}^{n} P_{\mathrm{eva}}^t \le \Delta Q_{\mathrm{eva}}^w. \tag{12}$$

(4) Because the battery is the core of EV and its cost is very expensive, consider the fact that the battery life will greatly reduce when it is repeatedly started and stopped in a short time [8]. Therefore, a continuity discharging condition for EVA's battery is introduced.

$$P_{\mathrm{eva}}^t > 0. \tag{13}$$

2.5. Two-Objective Optimization Model. Based on the above formulae, the optimization scheduling of EVs discharging can be expressed as a two-objective optimization issue with constraints:

$$\begin{aligned} \max \quad & F_1\left(P_{\mathrm{eva}}^w\right) = \max\left(C_1 - C_2\right), \\ \max \quad & F_2\left(P_{\mathrm{eva}}^w\right) = \max\left[\mu\sum_{t=1}^{n}\left(e_t - e_0\right)P_{\mathrm{eva}}^t\right], \end{aligned} \tag{14}$$

$$\begin{aligned} \text{S.T.} \quad & P_{\mathrm{eva}}^t \le \frac{P_r^{\max}}{\max\left(k_{\mathrm{ev}}^i\right)}, \quad t = 1,\ldots,n \\ & P_{\mathrm{eva}}^t \le P_{\mathrm{st}}^t \\ & \sum_{t=1}^{n} P_{\mathrm{eva}}^t \le \Delta Q_{\mathrm{eva}}^w \\ & P_{\mathrm{eva}}^t > 0. \end{aligned} \tag{15}$$

3. Solution

3.1. Multiobjective Simplified Method. In this paper, the optimization scheduling of EVs discharging is a multiobjective optimization problem which not only decreases the basic tariff for producer but also improves the benefits of EV discharging. Since the multiobjective optimization problem is a set for a group or several groups of solutions, however, there is no true optimal solution even if each target function can achieve optimum. Thus, the optimization goals in this article can be fuzzed by the selected membership function method instead of the weighted method due to the relative importance of the two-objective functions being difficultly determined [10]. After being fuzzed, the multiobjective optimization problem can be converted into a single-objective optimization problem.

$$\min \quad f(X) = \min\max\{g[f_i(X)]\}, \quad i = 1, 2, \tag{16}$$

where $g[f_i(X)]$ is single-target membership value and $f_i(X)$ is single-target indicator value. A linear function is selected as the membership function, which is expressed as

$$g(f) = \begin{cases} 1, & f < f_{\min}, \\ \dfrac{f_{\max} - f}{f_{\max} - f_{\min}}, & f_{\min} \le f \le f_{\max}, \\ 0, & f > f_{\max}, \end{cases} \tag{17}$$

where $f_{\min}$ is an unacceptable value (in this paper, the unacceptable values of the two functions can be set to 0) and $f_{\max}$ is an ideal value.

3.2. Handling of Constraints. Penalty function method (PFM) is utilized to solve constrained optimization problem, which can convert a constrained optimization problem into an unconstrained optimization problem [11]. This paper uses the external point method for handling the constraints.

3.3. Single-Objective Unconstrained Optimization Model. According to the multiobjective simplified method and the penalty function method, a single-objective unconstrained optimization model can be expressed as

$$\begin{aligned} &F(P_{\text{eva}}^{w}) \\ &\quad = \min\max\{g[f_i(P_{\text{eva}}^{w})] + o(P_{\text{eva}}^{w})\}, \quad i = 1, 2 \\ &o(P_{\text{eva}}^{w}) = r^{\text{num}} \sum_{k=1}^{4} \sum_{t=1}^{n} \Phi\{H_k[P_{\text{eva}}^{t}]\}, \\ &r^{\text{num}} = \alpha^{\text{num}}, \quad \text{num} = 1, \dots, M, \end{aligned} \tag{18}$$

where $o(P_{\text{eva}}^{w})$ is a penalty term; $\Phi\{\cdot\}$ is a penalty function; r^{num} is a penalty factor (the initial value can be set to $r^0 = 8$); num is number of iterations; M is the maximum number of iterations; and α is a value of experience which is usually set to 5~10, and this paper sets its value to 8 [12].

3.4. Improved Artificial Fish Swarm Algorithm (IAFSA). Solving optimization scheduling problem of EV discharging is a multidimensional, multivariable, nonlinear optimization process, which is difficult to be solved by a linear programing method or other classic optimization algorithms. An artificial fish swarm algorithm (AFSA), which is a good solution to address the issue, is a stochastic search algorithm which constructs artificial fishes and imitates diverse behaviors including swarming behavior, rear-end behavior, foraging behavior, and random behavior to achieve global optimization [13]. However, AFSA has some shortcomings:

(i) The accuracy of calculated solution by AFSA is low due to the fixed parameters (e.g., the visual range R_V and moving step Δ need to be set fixed values before executing the algorithm).

(ii) There are some flaws in behaviors of artificial fishes (e.g., the foraging behavior of artificial fish in AFSA was executed many times in each iteration, which can reduce the calculation speed of the AFSA).

To overcome these shortcomings, paper [14] not only introduced adaptive parameters to improve the accuracy but also improved artificial fish behaviors to improve the program efficiency. Thus the improved artificial fish swarm algorithm (IAFSA) combined with the penalty function methods was applied to solve the model. The following are the specific procedures.

Step 1. Initialize basic parameters, including number of artificial fish N_A, visual range R_V and minimum visual range $R_{V\min}$, moving step Δ and minimum moving step $\Delta_{\min}$, crowding factor δ, maximum attempt times N_T, penalty factor r, and maximum number of iterations M.

Step 2. According to the objective functions and constraints, construct the penalty functions and generate the augmented functions for two single-objective functions.

Step 3. Initialize the location of each generated artificial fish. If the generated artificial fish is not an external point, then use the temporary objective function for correction.

Step 4. Calculate each augmented objective function value according to the location of each generated artificial fish. Select the best individual and then insert it into the bulletin board. Set the number of iterations to 1.

Step 5. According to the current number of iterations, calculate the penalty factor using (18). Move each artificial fish and executive diverse behaviors including swarming behavior, rear-end behavior, foraging behavior, and random behavior. Select the location of optimal artificial fish behavior as that of each artificial fish. Then calculate each augmented objective function value according to the location of each moved artificial fish and judge whether it is a better individual compared to the one from bulletin board. If so, update the data of bulletin board.

Step 6. Add 1 to number of iterations and judge whether it is equal to the maximum number of iterations. If so, stop iterating and set the value from bulletin board to the optimal solution for single-objective optimization; if not, go to Step 5.

Step 7. Based on the obtained optimization results from the above steps $f_{1\max}$ and $f_{2\max}$, simplify processing for multiobjective functions in this paper using (17).

Step 8. Set parameters of the optimization problem after simplification process. According to the simplified objective function and constraints, construct the penalty functions and generate the augmented function.

Table 1: Configuration of dischargers.

Index	Value
P_r^{max}	10 (kW)
η_d	0.9
C_w	1000 (Yuan/per one)
k_w	0.03
C_m	75 (Yuan/per one)

Table 2: Parameters of several typical EVs.

Type	Battery capacity (kWh)	Mileage (km)	Proportion (%)
Zotye5008EV	32.0	180	8.24
Nissan Leaf	24.0	150	19.85
Roewe E50	18.0	160	16.55
BJ-E150	25.6	180	26.47
BYD-E6	65.0	280	28.89

Step 9. Repeat Steps 3 to 6.

4. Numerical Simulation

In this study, the whole optimization period is set to 8:00–18:00 and divided into 10 sections with the duration of one hour. Besides, it is assumed that there are 400 EVs needed to be discharged in an office parking lot.

4.1. Parameter Settings of Simulation

4.1.1. Configuration of Dischargers. In order to meet the discharging demands of EVs, the configuration of dischargers for EVs charging station is set in Table 1.

4.1.2. Configuration of EVs. At present, there are several typical EVs at home and abroad in Table 2, where the proportion of EVs is calculated according to the sales of different types of EVs.

Due to the short mileage between home and office, the initial SOC of EVs at office is assumed to follow approximately normal distribution whose mean value and standard deviation equal 0.8 and 0.03 and the expected SOC of EVs battery is set to 0.5.

4.1.3. Typical Daily Load of a Producer. A typical daily load curve of a producer before regulation can be predicted and the average value per hour of load is shown in Figure 2.

4.1.4. Data of Price. According to [2], the basic tariff for producer is set to 40.5 [Yuan/(kW·month)] and the valley and peak prices for users are 0.307 (Yuan/kWh) in 22:00–6:00 and 0.617 (Yuan/kWh) in 6:00–22:00 in residential areas. Because the price for producers in working time is higher than that for EV users in residential areas, this paper set EV discharging price to the TOU price in a production unit during working time, which is shown in Figure 3.

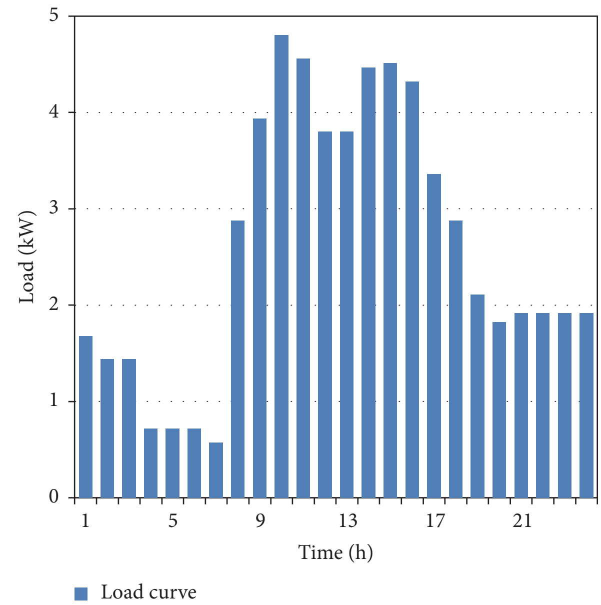

Figure 2: A typical daily load curve of a producer.

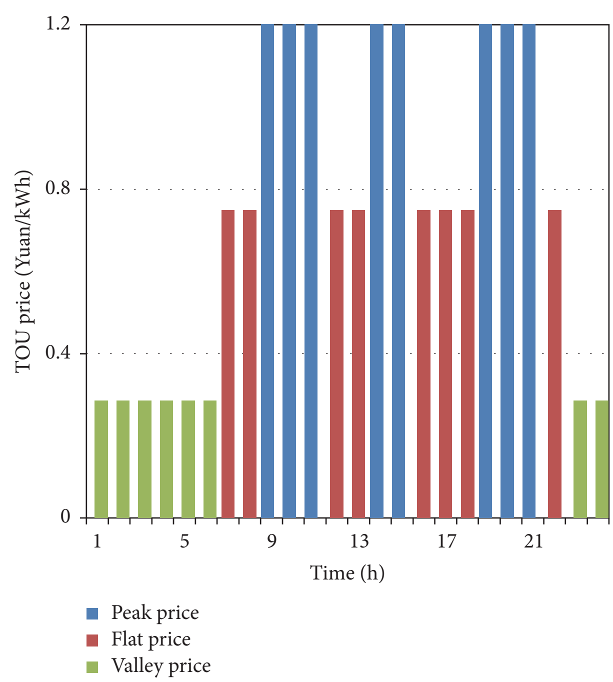

Figure 3: TOU price in a production unit.

Table 3: Parameters of IAFSA.

Parameter	N_A	R_V	Δ	δ	M	$R_{V\min}$	$\Delta_{\min}$	N_T
Value	50	330	40	0.618	200	33	4	10

4.1.5. Parameters of IAFSA. The parameters of IAFSA algorithm are set as shown in Table 3.

4.2. The Results and Analysis of Simulation. Based on parameter settings of simulation, the single-objective unconstrained

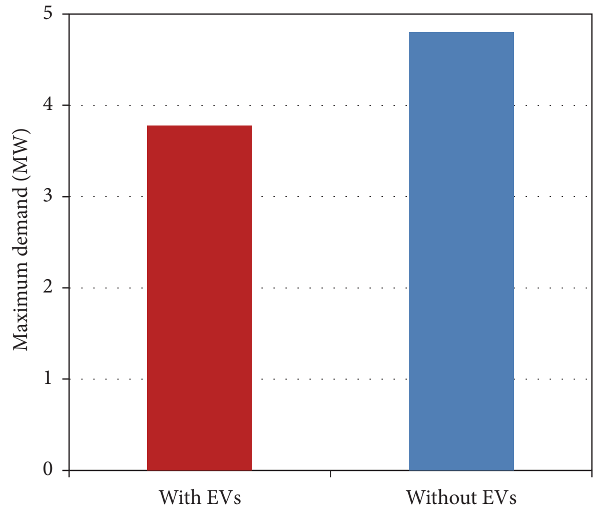

Figure 4: Maximum demands for producer with and without EVs (shorter bar is better).

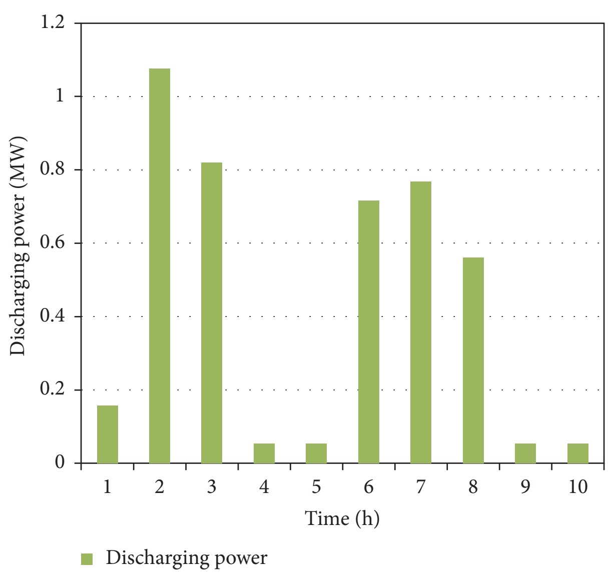

Figure 5: Optimal discharging power for EVA for each period.

optimization model established previously is solved by the IAFSA and the results of simulation can be shown as follows.

4.2.1. Comparison of the Cases of Unit with and without EVs. Figure 4 presents the maximum demands for producer with and without EVs. It shows that the maximum demand indeed decreases with EVs by EV orderly discharging strategy, going from 4.8 MW to 3.7785 MW. This is a decrease of 21.28% in the maximum demand of producer. Furthermore, the calculated annual earnings and cost for EVs charging station are listed in Table 4.

Table 4 clearly indicates that the annual earnings for EVs charging station ($C_1 - C_2$) are 454,466 (Yuan); in other words, the basic tariff for producer has been reduced by 19.48%. It shows that the production unit can obviously acquire profit from the EVs discharging.

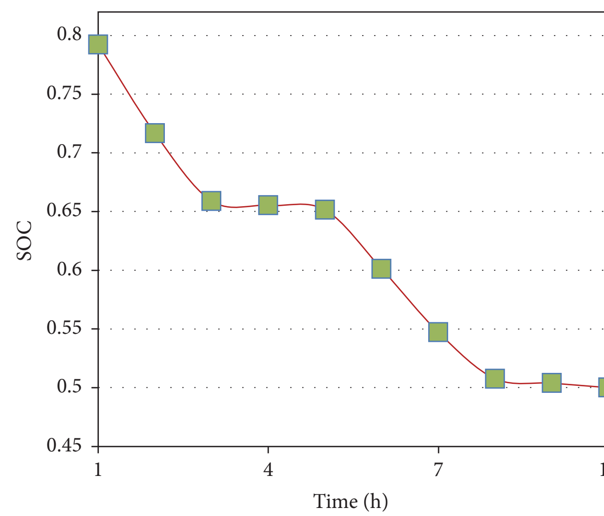

Figure 6: The SOC of EVA for each period.

Table 4: Calculated annual earnings and cost for EVs charging station.

C_1 (Yuan)	C_2 (Yuan)	$C_1 - C_2$ (Yuan)
496,466	42,000	454,466

4.2.2. Optimal Discharging Pattern and SOC for EVA. The optimal solution obtained by IAFSA is regarded as the orderly discharging strategy for EVs and the optimal discharging power for EVA for each period is shown in Figure 5.

Figure 5 shows that most of EVs' discharging energy is supplied to the electricity elements of the production unit during 9:00~11:00 and 13:00~16:00. The game point between the producer and EV users is that though discharging price for EVs in 15:00~16:00 is not the highest, controlled EVs still discharge a lot in this period when the load for producer plays an important role in reducing the maximum demand. Therefore, the EV orderly discharging strategy can bring benefits for the producer and the EV users.

According to formulae (4) and (5), the SOC of the EVA battery can be computed and its discharging curve is shown in Figure 6. From Figure 6, the SOC of EVA battery is closed to be 0.5 (the expected SOC of EVs battery) at the end of the whole optimization period discharged by orderly discharging strategy. It is confirmed that the optimal pattern can meet the demands of EVs discharging commendably. In addition, the annual discharging earnings for EVs are 1,158,276 (Yuan).

5. Conclusions

The orderly discharging strategy has been studied. In order to reduce the basic tariff of producer and improve the total benefits of EV discharging, a two-objective optimization model is established by controlling EVs discharging power during discharging process. Then a membership function method can be applied to converting multiobjective optimization issue into a single-objective optimization issue. Furthermore, an improved artificial fish swarm algorithm (IAFSA) combined with the penalty function methods was applied to solve the model. Finally, the results of simulations show that the obtained orderly discharging strategy is effective and reliable. Under this strategy, the maximum demand and basic tariff for producer have been reduced by 21.28% and 19.48% and the profit for EV users can be acquired.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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