Optimal Operation of Energy Internet Based on User Electricity Anxiety and Chaotic Spatial Variation Particle Swarm Optimization

Dongsheng Yang, Qianqian Chong*, Bo Hu, and Min Ma

Abstract: Ignoring load characteristics and not considering user feeling with regard to the optimal operation of Energy Internet (EI) results in a large error in optimization. Thus, results are not consistent with the actual operating conditions. To solve these problems, this paper proposes an optimization method based on user Electricity Anxiety (EA) and Chaotic Space Variation Particle Swarm Optimization (CSVPSO). First, the load is divided into critical load, translation load, shiftable load, and temperature load. Then, on the basis of the different load characteristics, the concept of the user EA degree is presented, and the optimization model of the EI is provided. This paper also presents a CSVPSO algorithm to solve the optimization problem because the traditional particle swarm optimization algorithm takes a long time and particles easily fall into the local optimum. In CSVPSO, the particles with lower fitness value are operated by using cross operation, and velocity variation is performed for particles with a speed lower than the setting threshold. The effectiveness of the proposed method is verified by simulation analysis. Simulation results show that the proposed method can be used to optimize the operation of EI on the basis of the full consideration of the load characteristics. Moreover, the optimization algorithm has high accuracy and computational efficiency.

Key words: Electricity Anxiety (EA); Energy Internet (EI); chaotic spatial variation particle swarm optimization; optimal operation

1 Introduction

With the excessive consumption of traditional fossil fuels and increasing environmental problems, Energy Internet (EI) is becoming a focused development direction of energy systems, which includes a large number of Renewable Energy Sources (RESs) and Distributed Generators (DGs) as the representative of the new energy technology and with networking, big data, and cloud computing as the representative of Internet technology[1, 2]. The diversity and complexity of DGs and loads in EI lead to significant differences between EI and the traditional power systems. EI research mainly includes the design of the system architecture, capacity allocation of DGs, and coordinated optimal operation of generation-grid-load[3]. In EI, some loads can participate in the optimization of the operation to perform peak shaving and valley filling and to improve system stability and economy. Thus, the control of the generation and the demand for the optimal operation of EI have become a top priority in the field of EI research.
This paper divides the load into four categories: Critical Load (CL), Translation Load (TL), Shiftable Load (SL), and Temperature Load (TPL). However, users might be more concerned about their own feelings. Controlling power consumption will cause anxiety in users, thereby seriously affecting their motivation to participate in demand response. Moreover, results will fail to achieve the maximum benefit of entire EI systems. Therefore, the study of EI optimal operation on the basis of user demand is of significant importance.

Currently, numerous studies have been conducted on the optimal operation of EI. Wu et al.\cite{4} and Huang et al.\cite{5} took the minimum operating cost as the goal to optimize EI operation, which increased the benefit of EI, but they did not consider the demand response. Zhang et al.\cite{6}, Wu et al.\cite{7}, and Zhou et al.\cite{8} considered the coordinated optimal control of the generation-grid-load in the EI, but they did not classify or model the appliance. As a result, the optimization results were not in line with the actual situation. Igualada et al.\cite{9} proposed the concept of user power mileage anxiety of Electric Vehicles (EVs). This concept can better reflect user mentality and behavior than user satisfaction. However, the anxiety model of other load types has not been established, and it cannot accurately reflect the user’s electricity habits. For the multi-objective optimization algorithm, many scholars have presented an improved optimization method. Li et al.\cite{10} combined PSO with chaos theory, and the randomness and ergodicity of the particles were improved. However, the optimization process was premature and stagnant. As a result, the final result did not achieve the global optimum. Zhong et al.\cite{11} introduced cross mechanism into PSO. Although the diversity of population particles increased, the method still had the disadvantage of being unable to obtain the global optimum.

To address the shortcomings of current research, this paper proposes an EI optimization method based on users’ Electricity Anxiety (EA) and Chaotic Space Variation Particle Swarm Optimization (CSVPSO), which takes the comprehensive cost of EI and the EA of users as the objective function and the system power balance as the constraints. CSVPSO is used to optimize the model. A simulation study is presented to validate the proposed method. The remainder of this paper is organized as follows: Section 2 establishes the load models and introduces the optimal operation model of EI. Section 3 presents the proposed CSVPSO algorithm. Section 4 provides a detailed case study and discussions. Finally, Section 5 concludes the paper.

### 2 Model

#### 2.1 EI system architecture

The EI system is mainly composed of RES, Microgrid (MG), Power Grid (PG), and load units. The generators of EI include Photovoltaic Panels (PVs), Wind Turbines (WTs), Gas Turbines (GTs), and Battery Storages (BSs). The EI system architecture is shown in Fig. 1.

In Fig. 1, $P_{PV,t}$, $P_{WT,t}$, and $P_{GT,t}$ represent the power output of PV, WT, and GT at time $t$, respectively; $P_{Con,Cri,t}$, $P_{Tra,t}$, $P_{Shi,t}$, and $P_{Tem,t}$ represent the power demand of CL, TL, SL, and TPL at time $t$, respectively; $P_{BS,t}$ represents the power charging/discharging by a battery at time $t$; and $P_{Grid,t}$ and $P_{Micro,t}$ represent the exchange power between EI and PG and between EI and MG at time $t$, respectively. To simplify the calculation, this paper considered only the power exchange between EI and PG. To make full use of RES, PVs and WTs both work in maximum power point tracking status.

#### 2.2 Load model

**1) Critical load**

CL has a fixed power demand and strong regularity, which is not controllable by a control center, such as lights and TV. The CL model can be expressed as follows.

\[
P_{Cri,t} = P_{Con,Cri,t} \quad (1)
\]

\[
P_{Cri,t} \leq P_{rate,Cri} \quad (2)
\]

where $P_{Con,Cri}$ is the constant power demand of CL, and $P_{rate,Cri}$ is the rated power of CL.

**2) Translation load**

TL power demand is fixed and its operating time...
cannot be interrupted. However, advancing or postponing
the startup time appropriately has less impact on user
demand. TL includes Washing Machines (WMs) and
dishwashers. The model can be expressed as follows:

\[ P_{T_{\text{tra}},t} = P_{\text{Con},T_{\text{tra}},t} \]  
(3)

\[ P_{\text{Con},T_{\text{tra}},t} \leq P_{\text{rate},T_{\text{tra}}} \]  
(4)

\[ T_{\text{tra}}^S \leq T_{\text{tra}}^E \]  
(5)

\[ T_{\text{tra}}^E - T_{\text{tra}}^S = T_{\text{Con},T_{\text{tra}}} \]  
(6)

where \( P_{\text{Con},T_{\text{tra}},t} \) represents the constant power demand of TL; \( P_{\text{rate},T_{\text{tra}}} \) is the rated power of TL; \( T_{\text{tra}}^S \) and \( T_{\text{tra}}^E \) represent the actual beginning time and stopping time of the operation of TL, respectively; \( T_{\text{tra}}^{\text{Def},S} \) is the expected beginning time of the user; \( T_{\text{tra}}^{\text{Def},E} \) is the end of the scheduling cycle; and \( T_{\text{Con},T_{\text{tra}}} \) represents the constant operating time of TL.

(3) Shiftable load

Unlike TL, SL has no limitation of timing and continuity. In the range of power demand and the acceptable transfer time, the beginning time, the operating time, and the stopping time can be flexibly scheduled according to the users’ requirement and the electricity tariff. Such load includes EVs and Energy Storage Systems (ESSs). The SL model can be expressed as follows:

\[ P_{\text{Shi},t} \leq P_{\text{Shi},t} \leq P_{\text{rate},Shi} \]  
(7)

\[ E_{\text{Sum},\text{Shi}}^S = \sum_{t=1}^{T_{\text{Shi}}} P_{\text{Shi},t} \cdot v_t \cdot (T_{\text{Shi},t}^E - T_{\text{Shi},t}^S) \]  
(8)

where \( P_{\text{Shi},t} \) is the lower power limit of SL; \( P_{\text{rate},Shi} \) is the rated power of SL; \( T_{\text{Shi},t}^S \) is the stopping time of SL; \( T_{\text{Shi},t}^E \) is the beginning time, and \( T_{\text{Shi},t}^E - T_{\text{Shi},t}^S \) is the operating time; \( v_t \) is the operating state at \( t \) time; and \( v_t = 1 \) represents that the load is in a running state; \( E_{\text{Sum},\text{Shi}}^S \) is the power status at the end of the scheduling cycle; \( E_{\text{Shi}}^{\text{Def},t} \) is the expected power load status of the user; \( E_{\text{Shi}}^{\text{rate}} \) is the rated power state of the load; \( T_{\text{Shi},t}^{\text{min}} \) is the minimum continuous operating time; and \( [T_{\text{Shi},t}^S, T_{\text{Shi},t}^E] \) is the acceptable transferring interval of SL.

(4) Temperature load

The operating characteristics of TPL mainly depend on the difference of indoor and outdoor temperature, such as Air Conditioning (AC) and cold storage equipment. TPL power demand is not fixed. The users are able to adjust the operating power according to their own demand. The TPL model can be expressed as follows:

\[ 0 \leq P_{\text{T}_{\text{tem}},t} \leq P_{\text{rate},t} \]  
(12)

\[ T_{\text{t+1}}^\text{in} = \kappa_1 T_{\text{t}}^\text{in} + (1 - \kappa_1) \left( T_{\text{t}}^\text{out} - \kappa_2 P_{\text{T}_{\text{tem}},t} \right) / \omega \]  
(13)

\[ T_{\text{t+1}}^\text{in} \leq T_{\text{t+1}}^\text{in} \leq T_{\text{Exp}}^\text{Set} \]  
(14)

where \( P_{\text{T}_{\text{tem}},t} \) is the power demand of TPL at \( t \) time; \( P_{\text{rate},t} \) is the rated power of TPL; \( T_{\text{t+1}}^\text{in} \) is the indoor temperature at \( t+1 \) time interval; \( T_{\text{t+1}}^\text{in} \) and \( T_{\text{t+1}}^\text{out} \) represent the indoor temperature and outdoor temperature at \( t \) time interval, respectively; \( \kappa_1 \) is the inertial coefficient of the changing of indoor temperature; \( + \) and \( - \) represent the heating and cooling mode of TPL; \( \kappa_2 \) is the heat conduction efficiency; \( \omega \) is the coefficient of heat conduction; and \( T_{\text{Exp}}^\text{min} \) and \( T_{\text{Exp}}^\text{max} \) are the upper and lower indoor temperature limit allowed by the user.

2.3 Optimal operation model of EI

2.3.1 Objective model

The objective model takes the comprehensive EI cost and user EA as the objectives. The utility model realizes the economical optimal operation of each unit in the EI system under the condition of minimizing the user EA.

(1) Comprehensive EI cost

The comprehensive EI cost can be expressed as follows:

\[ C_{\text{EI},t} = \sum_{i \in N_{FL}} C_{i,t}^{FL} + \sum_{i \in N_{OM}} C_{i,t}^{OM} + \sum_{i \in N_{BS}} C_{i,t}^{BS} + C_{i,t}^{Com} + C_{i,t}^{Grid} \]  
(15)

where \( C_{\text{EI},t} \) is the comprehensive EI cost; \( C_{i,t}^{FL} \) is the primary energy cost; \( C_{i,t}^{OM} \) is the operation and maintenance cost of the units; \( C_{i,t}^{BS} \) is the loss cost of battery charging/discharging process; \( C_{i,t}^{Com} \) is the environmental cost; \( C_{i,t}^{Grid} \) is the exchange cost between EI and PG; \( N_{FL} \) and \( N_{BS} \) represent the collection of fuel cells and batteries, respectively; \( C_{i,t}^{Com} \) is the compensation expenses for the participation of load \( j \) in the optimized operation; and \( N_{FL} \) is the collection of TL, SL, and TPL.

1) Primary energy cost

\[ C_{i,t}^{FL} = \sum_{t=1}^{T} C_{i,t} \cdot \frac{P_{i,t}}{H_{i,t}} \]  
(16)

where \( C_{i,t} \) is the unit primary energy price; \( H_{i,t} \) is the calorific value of primary energy; \( P_{i,t} \) is the power
delivered by DG $i$ at time $t$; and $\eta_{i,t}$ is the conversion efficiency of DG $i$ at time $t$. The primary energy price of PV and WT is considered as zero.

2) Operation and maintenance cost

$$C_{Om,i,t} = \sum_{t=1}^{T} k_{Om,i} P_{i,t}$$  \hspace{1cm} (17)

where $k_{Om,i}$ is the cost coefficient of the operational maintenance of DG $i$ when providing unit power\cite{12,13}.

3) Loss cost of the battery charging/discharging process

$$C_{Ev,BS} = \sum_{t=1}^{T} \gamma_{BS} \frac{\Delta S_{i,t}}{S_{i}^{\text{max}} - S_{i}^{\text{min}}} C_{t}^{}$$  \hspace{1cm} (18)

where $\gamma_{BS}$ is the correction factor; $\Delta S_{i,t}$ is the variable quantity of SOC in the charging/discharging process; $S_{i}^{\text{max}}$ and $S_{i}^{\text{min}}$ are the maximum and minimum SOC status of the battery; $C_{t}$ is the purchasing expense of the battery; and $\Delta N$ is the maximum cycle index of the battery.

4) Environmental cost

$$C_{Ev} = \sum_{t=1}^{T} \sum_{u=1}^{U} 10^{-3} \beta_{u} \alpha_{Grind,u} P_{i,t}^{DS}$$  \hspace{1cm} (19)

where $\beta_{u}$ is the penalty cost for the emission of the pollutants and greenhouse gases considered in this paper, including NO$_x$, SO$_2$, and CO$_2$; and $\alpha_{Grind,u}$ is the emission coefficients of pollutant $u$\cite{14}.

5) The exchange cost

$$C_{Grid}^{\text{Grind}} = r_{Grind,t} P_{Grid,t}$$  \hspace{1cm} (20)

where $r_{Grind,t}$ is the swapped power cost between EI and PG.

6) Compensation expense

$$C_{Com,j,t} = \sum_{t=1}^{T} C_{Com,j} \Delta P_{j,t}$$  \hspace{1cm} (21)

where $C_{Com,j}$ is the compensation expense for load $j$, and $\Delta P_{j,t}$ is the amount of power transferring and shedding of load $j$ after optimization at $t$ time interval.

(2) User EA

The user EA includes the electric cost anxiety and the electric consumption mode anxiety. The electric cost anxiety means the least electricity bill is paid on the basis of meeting the power demand. The electric consumption mode anxiety is caused by the inconsistency between the operation of the electrical appliances and user expectations. The EA can be expressed as follows:

$$C_{Anx,t} = C_{Coin}^{Anx,t} + C_{Wag}^{Anx,t}$$  \hspace{1cm} (22)

where $C_{Anx,t}$ is the user EA; $C_{Coin}^{Anx,t}$ is the electric cost anxiety; and $C_{Wag}^{Anx,t}$ is the electric consumption mode anxiety.

1) Electric cost anxiety

$$C_{Coin}^{Anx,t} = \frac{\sum_{t=1}^{T} \sum_{j \in N_{load}} c_{j,t} P_{j,t}^{'} - \sum_{t=1}^{T} \sum_{j \in N_{load}} C_{Com,j} \Delta P_{j,t}}{\sum_{t=1}^{T} \sum_{j \in N_{load}} c_{j,t} P_{j,t}^{'}}$$  \hspace{1cm} (23)

where $c_{j}$ is the electric tariff of EI at $t$ time; $P_{j,t}^{'}$ is the power consumption of load $j$ after optimization at $t$ time; $P_{j,t}$ is the power consumption of load $j$ before optimization at $t$ time.

2) Electric consumption mode anxiety

The electric consumption mode anxiety of TL mainly depends on its starting time, i.e., a later starting time corresponds to great anxiety. The electric consumption mode anxiety function of TL is

$$C_{Tri}^{Anx,t} = \begin{cases} 0, & \text{if } \Gamma_{Tri} = \Gamma_{Tri}^{max}, \Gamma_{Tri}^{'} \leq \Gamma_{Tri}^{max}; \\
\frac{\Gamma_{Tri}^{max} - \Gamma_{Tri}^{'} + \Gamma_{Tri}^{max} - \Gamma_{Tri}^{'} - \Gamma_{Tri}^{max}}{\Gamma_{Tri}^{max}}, & \text{if } \Delta \Gamma \leq \Gamma_{Tri}^{max} \leq \Gamma_{Tri}^{max}; \\
\frac{\Gamma_{Tri}^{max} - \Gamma_{Tri}^{'} + \Gamma_{Tri}^{max} - \Gamma_{Tri}^{'} - \Gamma_{Tri}^{max}}{\Gamma_{Tri}^{max}}, & \text{if } \Gamma_{Tri}^{max} < \Gamma_{Tri}^{max} \leq \Gamma_{Tri}^{max} \leq \Gamma_{Tri}^{max}
\end{cases}$$  \hspace{1cm} (24)

where $C_{Tri}^{Anx,t}$ is the electric consumption mode anxiety of TL at time $t$; $\Gamma_{Tri} = \Gamma_{Tri}^{max} + \Gamma_{Tri}^{'}$, $\Gamma_{Tri}^{'}$ is the length of the user allowance of delay time, which means that if TL starts during $\Gamma_{Tri}^{'}$, the user will not generate anxiety; $\Gamma_{Tri}^{max} = \Gamma_{Tri}^{max} + \Gamma_{Tri}^{max} + \Gamma_{Tri}^{max}$ is the maximum length of time that the user can tolerate, which means that if TL starts during $\Gamma_{Tri}^{max}$, then the user will generate anxiety.

The user electric consumption mode anxiety function of SL mainly depends on its power status, i.e., a low power status corresponds to high anxiety. The electric consumption mode anxiety function of SL is

$$C_{Shi}^{Anx,t} = \begin{cases} 0, & \text{if } E_{Shi}^{Def,f} - E_{Shi}^{Def,Q} + E_{Shi}^{Def,f} \leq E_{Shi}^{Def,f}; \\
\frac{E_{Shi}^{Def,f} - E_{Shi}^{Def,Q} + E_{Shi}^{Def,f} - E_{Shi}^{Def,f}}{E_{Shi}^{Def,f}}, & \text{if } \Delta E \leq E_{Shi}^{Def,f} \leq E_{Shi}^{Def,f}; \\
\frac{E_{Shi}^{Def,f} - E_{Shi}^{Def,Q} + E_{Shi}^{Def,f} - E_{Shi}^{Def,f}}{E_{Shi}^{Def,f}}, & \text{if } E_{Shi}^{Def,f} < \Delta E \leq E_{Shi}^{Def,f}
\end{cases}$$  \hspace{1cm} (25)

where $C_{Shi}^{Anx,t}$ is the electric consumption mode anxiety of SL at time $t$; $\Delta E = E_{Shi}^{Def,f} - E_{Shi}^{Def,Q}$, $E_{Shi}^{Def,f}$ is the power...
shedding allowed by the user, which means that if the load 
power reduction amount is within the limit, then the user 
will not generate anxiety, or the user will have anxiety; 
$E_{Shi}^t$ is the initial power state of SL.

The user electric consumption mode anxiety of TPL 
mainly depends on the indoor temperature, which means 
that there is a great difference between the indoor temperature 
and the expected temperature of the user corresponds to high 
anxiety. The electric consumption mode anxiety function 
of TPL is

$$C_{Anx,t}^{Tem} = \begin{cases} 
1 + \frac{T_{min}^i - T_{in}^i}{T_{in}^i - T_{Exp}^i}, & T_{in}^i < T_{min}^i \cap T_{max}^i \geq T_{Def} \cap T_{Exp} < T_{in}^i, \\
0, & T_{min}^i \leq T_{in}^i \leq T_{max}^i \cap T_{Exp} \geq T_{in}^i, \\
1 + \frac{T_{max}^i - T_{in}^i}{T_{Exp}^i - T_{in}^i}, & T_{in}^i > T_{max}^i \cap T_{Exp} < T_{min}^i
\end{cases} (26)$$

where $C_{Anx,t}^{Tem}$ is the electric consumption mode anxiety of 
TPL at $t$ time; $T_{min}^i$ and $T_{max}^i$ are the upper and lower 
limits of the most comfortable temperature defined by the 
user, which means that within the range, the user will not 
generate anxiety, otherwise, the user will have anxiety.

Thus, the electric consumption mode anxiety of the 
user can be expressed as

$$C_{Anx,t}^{Way} = \lambda_1 C_{Anx,t}^{Tem} + \lambda_2 C_{Anx,t}^{Shi} + \lambda_3 C_{Anx,t}^{Tem} (27)$$

where $\lambda_1$, $\lambda_2$, and $\lambda_3$ are the weight coefficients, all of 
which are equal to $1/3$.

3. EI optimization objective model

To simplify the calculation process, the two objective 
functions with different dimensions are treated in a 
dimensionless way[15]. With Eqs. (15) and (22) combined, 
the single objective function can be expressed as

$$\min \sum_{i=1}^{24} \sqrt{\alpha[C_{E,i}]^2 + \beta[C_{Anx,t}]^2} (28)$$

where $\alpha$ and $\beta$ are the weight coefficients, which indicate 
the degree of the emphasis of the single objective function 
on the comprehensive EI cost and user EA. To fit the 
amplitude difference of the multi-objective function, $\alpha = 1$, $\beta = 10$.

2.3.2 Constraint condition

1. Power output constraint

$$P_{i,min}^t \leq P_{i,t} \leq P_{i,max}^t (29)$$

where $P_{i,min}^t$ and $P_{i,max}^t$ are the upper and lower power limits 
of DG $i$, respectively.

2. Battery storage constraint

$$S_{i,min}^t \leq S_{i,t} \leq S_{i,max}^t (30)$$
where $\omega^k$ is the chaotic inertia weight in the $k$-th iteration; $\alpha^k$ is the chaotic parameter in the $k$-th iterations; $\mu$ is the control parameter; and the state of the system can be controlled by varying $\mu$.

Next, the cross operation of the position is performed for the particles with poor fitness. The particle fitness values are sorted from high to low, and the particles are divided into two subgroups $m_1$ and $m_2$ according to the fitness values. The particles of $m_2$ with poor fitness values are crossed to produce offspring. Comparing the offspring with their parents, half of the particles with high fitness values are selected to form a new group $m_3$. The particles of $m_1$ and $m_3$ move into the next generation, thereby improving the diversity of particles. The cross operation of the particle position can be expressed as follows:

$$x_{\text{child},i}^k = (1 - \beta_1) x_{\text{parent},i}^k + \beta_1 x_{\text{parent},j}^k$$  \hspace{1cm} (38)

where $x_{\text{child},i}^k$ is the position of offspring $l$; $\beta_1$ is a random number between $[0, 1]$; $x_{\text{parent},i}^k$ and $x_{\text{parent},j}^k$ are the position of parent $i$ and parent $j$ for cross operation, respectively.

Finally, the spatial variation operation is introduced into the Chaotic PSO (CPSO). When the particle update speed is less than the set threshold $\Delta v$, the velocity of the particle is mutated to improve the convergence speed and to prevent them from falling into the local optimum solution. The variation of a particle’s velocity can be expressed as follows:

$$v_i^k \leftarrow (1 - \beta_2) v_i^k + \beta_2 v_{\text{rand}}^k$$  \hspace{1cm} (39)

where $v_{\text{rand}}^k$ is a random value of velocity in the $k$-th iteration; $\alpha$ is a constriction factor used to make sure that $v_{\text{rand}}^k$ is within the search space, and the value of $\alpha$ should not be too small, which may decrease the particle’s global searching ability. Moreover, this value should not be too large, as it may cause the particle to miss the location of the optimal solution. Thus, this paper takes $\alpha \in [0.5, 0.9]$.

With the use of CSVPSO to optimize the optimal operation model of EI, the position variables of the particles are set to six dimensional vectors, which represent six parameters of the optimization model: $\Phi = (P_{GS,t}, P_{BS,t}, P_{Grid,t}; P_{T_{\text{e}},t}, P_{Shi, t})$. The global optimum is obtained by using CSVPSO, which is the optimal value of the six parameters.

The flow chart of CSVPSO is shown in Fig. 2.

4 Simulation and Analysis

4.1 Parameters

The simulation parameters of a regional EI are as follows: the rated power limit of WT is 50 kW, and the lower limit is 0; the rated power limit of PV is 50 kW, and the lower limit is 0; the rated capacity of BS is 100 kWh, and the lower limit is 20 kWh; the upper and lower power limits of the GT are 50 and 0 kW; the peak load of the system is 90.35 kW, which operates at 18:00-19:00; the valley load of the system is 25.69 kW, which operates at 04:00-05:00; the particle number of the algorithm is 100, and the number of iterations is 100 times. On the basis of the objective

\begin{equation}
\Phi_{\text{opt}} = \min_{\Phi} \Phi
\end{equation}

\begin{equation}
v_{\text{rand}}^k = \alpha \cdot (x_{\text{max}} - x_{\text{min}})
\end{equation}

The power output constraints, battery constraints, power balance constraints are addressed.
function and decision variables, the typical curves of WT and PV and 4 different load data curves were collected, as shown in Figs. 3 and 4; with the use of the real time electricity tariff in this region\cite{21}, the electricity tariff is shown in Fig. 5. The contract data of controllable electrical appliances of a user involved in the system optimal operation are shown in Table 1.

4.2 Analysis of operation results of a typical user with different electric anxiety modes

In this paper, the optimal operation results of EI are analyzed in four modes: mode 1 is the scheduling without consideration of EA; mode 2 is the scheduling with consideration of the electric consumption mode anxiety; mode 3 is the scheduling with consideration of the electric cost anxiety; and mode 4 is the scheduling with consideration of EA.

The optimized operation results of the typical user with different EA modes are shown in Table 2, and the load power variation curves are shown in Figs. 6a, 6b, and 6c.

Table 1 shows that in mode 2, the user electric consumption mode anxiety of three kinds of electric appliance is 0, and the electric cost anxiety is lower than that in mode 1. This situation occurred because in the user-defined offset range, according to the optimization objectives and constraints to participate in the optimization of the operation, the load is shifted, thereby decreasing the power costs. In mode 3, the electricity bills of three kinds of electric appliances are all reduced, and the total expenditure of WM, EV, and AC is reduced to 2.40, 15.50, and 63.63 cents, respectively. Compared with mode 2, the electricity bills are reduced by 67.35%, 69.99%, and 50.41%, respectively, because within the user allowance, EV and AC are transferred to the low price time interval to reduce the costs. However, this mode often causes user electric consumption mode anxiety to reach its maximum, and the corresponding value is 1. In mode 4, through the reasonable scheduling of electric appliance’s operating power and time and through a decrease in the user electric consumption mode anxiety, the user EA is reduced significantly. Compared with mode 1, the user electric consumption mode anxiety of EV and AC is increased to 33.2%, 10.5%, 20.1%, but the electric cost anxiety is reduced to $-71.1\%$, $-76.3\%$, and $-36.4\%$, and the EA is declined.
Table 2  Optimal operation results under different anxiety levels.

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Mode</th>
<th>Electric consumption mode anxiety</th>
<th>Electric cost anxiety</th>
<th>Electricity anxiety fees (cent)</th>
<th>Electricity expenditure (cent)</th>
<th>Compensation expenses (cent)</th>
<th>Total expenditure (cent)</th>
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<td>0.658</td>
<td>15.29</td>
<td>2.4</td>
<td>12.89</td>
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<td>A</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>150.08</td>
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<tr>
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<td>2</td>
<td>0</td>
<td>-0.145</td>
<td>-0.145</td>
<td>131.18</td>
<td>3.51</td>
<td>128.32</td>
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<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>-0.576</td>
<td>0.424</td>
<td>85.91</td>
<td>22.28</td>
<td>63.63</td>
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<tr>
<td></td>
<td>4</td>
<td>0.201</td>
<td>-0.364</td>
<td>0.163</td>
<td>108.38</td>
<td>12.93</td>
<td>95.45</td>
</tr>
</tbody>
</table>

Fig. 6  Load curves under different anxiety levels.

Figure 6 shows that after the user participated in the optimal operation, the SL and TPL power consumption in all modes declined. This decline occurred because the power consumption of EV and AC is large; this power consumption can be reduced as much as possible in the optimal operation. EV charging is transferred to the lower price period, and the charging time is dispersed to minimize the electricity expenditure. Once the WM is started, it cannot be interrupted, but it can be reasonably translated in the user allowable offset range, so that the electricity expenditure is also reduced. In terms of user electric consumption mode anxiety, the anxiety of mode 3 is higher than that of mode 4, and the minimum electric consumption mode anxiety is in mode 2.

4.3 Analysis of operation results of user groups under different electric anxiety patterns

This section considers the influence of different user anxiety patterns on the optimal operation of EI in this region. Table 3 provides the optimal operation results, which are denoted as types 1, 2 and 3. Type 0 represents the original demand, which does not consider user EA. Figures 7, 8, and 9 show the load contrast curves, the GT output contrast curves, and the battery charging/discharging contrast curves of the three modes, respectively. In Fig. 9, the positive value indicates that the battery is in a charging state, and the negative value indicates that the battery is in a discharging state.

As shown in Table 3, with the increase in the user electric consumption mode anxiety, the user electric cost anxiety decreases, and the EA shows a rising trend after the first drop. The load peak value decreases by 7.26%, 8.92%, and 11.13%, because SL and TPL participated in peak shaving for optimal operation. The comprehensive EI cost of the three types is reduced by 2261, 3069, and 4182 cents, respectively.
Table 3 Optimal operation results of user groups under different electrical anxieties.

<table>
<thead>
<tr>
<th>Type</th>
<th>Electric consumption mode anxiety</th>
<th>Electric cost anxiety</th>
<th>Comprehensive anxiety</th>
<th>Peak load (kW)</th>
<th>Valley load (kW)</th>
<th>Load shedding (kW)</th>
<th>Comprehensive cost (cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>90.35</td>
<td>25.69</td>
<td>0</td>
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<td>1</td>
<td>0.25</td>
<td>0.33</td>
<td>0.08</td>
<td>83.79</td>
<td>25.72</td>
<td>20.6</td>
<td>35015</td>
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<tr>
<td>2</td>
<td>0.5</td>
<td>0.46</td>
<td>0.04</td>
<td>82.29</td>
<td>27.72</td>
<td>41.8</td>
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<tr>
<td>3</td>
<td>0.75</td>
<td>0.55</td>
<td>0.2</td>
<td>80.29</td>
<td>29.22</td>
<td>60.2</td>
<td>33094</td>
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</tbody>
</table>

Figure 7 shows that the peak values of the load curves in the three types are all shifted. The load peaks shifted from 18:00-19:00 to 12:00-13:00, thereby making the load curve closely consistent with the RES output curve, and also ensured that the RES is consumed in a timely manner. The load transfer not only alleviates the power supply pressure of the evening peak, but also makes direct use of the excess PV and WT output during the day, which improves the utilization rate of RES and reduces the wind and solar curtailment.

Figures 8 and 9 show that the daily power supplies of GT all decreased in three types, and their outputs are more stable. The charging/discharging times and depth of BS are both decreased, and the corresponding loss is reduced. With the increase in EA, such effect is more significant.

Thus, considering the operation characteristics of loads, establishing a reasonable user EA model, and actively guiding users to participate in demand response, not only can reduce the user electricity expenditure on the basis of meeting users’ power demand, but also can adjust the load curve reasonably. This method will effectively promote RES consumption, reduce the power output of GT and charging/discharging cycles of BS, and improve the economic benefits of the system.

4.4 Algorithm analysis

In this paper, PSO, CPSO, and CSVPSO are used to analyze the EI optimal operation of type 1 in Section 4.3. The fitness curves of the three algorithms are shown in Fig. 10.

Figure 10 shows that PSO appears premature in the 50th generation, and the iteration stops and falls into the local optimum. Although CPSO improves the tendency of PSO to easily fall into the local optimum to some extent, its convergence accuracy and speed are still lower than...
those of CSVPSO. Therefore, the proposed CSVPSO can enhance the global searching ability of particles, accelerate the evolution of the algorithm, and improve the convergence accuracy.

5 Conclusion

This paper focuses on the interactive characteristics of the generation-grid-load in EI, and the loads are regarded as negative generations to participate in the optimal operation of EI. The loads are also classified and modeled on the basis of their features. Through the introduction of a more comprehensive user EA function, the effects of TL, SL, and TPL on the optimal operation of EI are studied. The main conclusions are as follows: First, on the basis of load characteristics, the user EA is analyzed from two aspects, namely user electric consumption mode and electric cost anxiety. EA makes the user habit more practical, and can provide data reference for better guidance to users for participation in demand response. Second, on the basis of CSVPSO, the EI operation is optimized and the convergence precision of particles and the speed of evolution are accelerated. The accuracy and speed of the optimization results are improved. Simulation results show that the proposed method is reasonable and effective in reducing user EA and achieving the maximum EI benefits.

References


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