Optimal Scheduling of Building Users Electricity Consumption Based on Improved Gravitational Search Algorithm

Lingzhi Yi¹, Yanfang Jia¹, Shengbing Li¹, Genping Wang² and Chengdong Zhang¹

ABSTRACT

At present, people are increasingly concerned about the problem of building load scheduling. For this problem, the building users are classified and the characteristic of building users is analyzed, a model of automatic demand response for building intelligent electricity scheduling is built and it is composed of several objective functions, such as economy, comfort and stability of family intelligent power. By building two populations include parasitic group and host group, memory and group information sharing ability about particles in particle swarm optimization are introduced to simulate biological parasitic behavior mechanism, an improved gravitational search algorithm is proposed. Finally, the veracity and effectiveness of the proposed algorithm are verified through the simulation.

Keywords: Gravitational search algorithm (GSA), double populations, automatic demand response, optimal operation.

INTRODUCTION

Since the 21st century, with the rapid development of the global economy and society, building households and electricity consumption are gradually increasing. People on the building automation equipment, intelligent as the representative of the intelligent building expectations are getting higher and higher. Smart Grid is a new power intelligent service network[1], power demand response [2] is based on the power supply and demand situation by stimulating the user side to change the original power consumption, so as to achieve the purpose of energy conservation and optimize balanced allocation of resources. Building micro-grid is a small power grid, it consists of distributed power, energy storage device and various types of AC load and DC load and so on [3]. User electricity system in the building micro-grid is an intelligent building network control system. It’s based on smart grid and intelligent buildings, and combine all power generation, electricity and power storage device into one under the tools of smart meter. Building users electricity system and Automatic Demand Response technology can be achieved automatic scheduling of the electricity load in the building [4-5].

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The gravitational search algorithm [6] is proposed by professor Echat Rashedi in 2009, which is a new heuristic intelligent optimization algorithm based on Newton's law of gravity and the interaction between particles. The algorithm has the advantages of simplicity and versatility. While GSA has many shortcomings of poor local search ability and premature convergence, this algorithm has yet to be further improved.

In this paper, the ADR model of building users' electricity consumption is established by considering the factors such as electricity tariff, comfort and peak valley difference of electricity consumption in building micro-grid users. The global memory and biomechanical mechanism are introduced into the gravitational search algorithm, and the improved gravitational search algorithm is used to optimize the model.

**MATHEMATICAL MODEL OF ELECTRICITY CONSUMPTION FOR BUILDING MICRO-GRID USERS**

**Building Micro-grid User Electricity System Structure**

The electricity consumption system of the building micro-grid mainly includes various parts such as electrical device, electric vehicle, battery pack, renewable energy, intelligent meter and so on. According to the various types of consumer behavior habits, the buildings will be divided into four categories of users, that is, ordinary home users, office workers, commercial users and vacant users. Among them, the more belong to ordinary home users, it refers to the family who normal electricity, it maintain a certain level of electricity consumption during the day, and the electricity consumption early decline in the evening. The office workers electricity mainly concentrated in the morning and evening, and the electricity consumption is low in the daytime. The commercial users are high electricity consumption in the daily. The vacant users only have a little electricity consumption from the loss of line, because this power situation can’t be controlled, so such users don’t participate in building electricity schedule. This article will be divided into six categories for each user's device in the intelligent buildings. That is the uncontrollable device, the interruptible device, the transferable device, the power generation device, the charging device and the energy storage device.

**Optimized Scheduling Model**

The electricity schedule model in building users [7] is as follows, it mainly includes the objective function and corresponding constraints.

**OBJECTIVE FUNCTION**

The goal of optimization is mainly related to economic objectives, comfort objectives and grid stability objectives. The overall objective function \( F \) can be expressed as:

\[
\min F = (C,U,D)
\]

(1)

Among them:
Where a day’s 24 hours is divided into $T$ time, assuming that there are $n$ users in the building. $C$, $U$ and $D$ are the user's total electricity bill, user dissatisfaction and peak valley differencerespectively, $C_i$ is the total electricity for the user $i$, $U_i$ is the user dissatisfaction for the user $i$, $N$ is the total number of users in the building, $M$ is the total number of electricity users in each building, $c_t$ is the grid’s real-time electricity price of the $t$ time, $P_{j,t}$, $u_{j,t}$ and $p_{j,t}$ are the actual power, user dissatisfaction and power of device $j$ at time $t$ respectively.

**THE SCHEDULABLE DEVICE CONSTRAINTS**

Building user device constraints mainly aim at the scheduling load. For the interruption device constraints, it’s mainly impacted by power and power off time, that is:

$$
\begin{align*}
    t_1 &\geq T_{on,i,\text{min}} \\
    t_2 &\leq T_{off,i,\text{max}}
\end{align*}
$$

(4)

Where $t_1$ represents the continuous running time, $t_2$ is the continuous power off time, $T_{on,i,\text{min}}$ and $T_{off,i,\text{max}}$ represent the shortest power-on time and the longest power-off time respectively.

The constraints on the transferable device are determined primarily by the device run time and the start and end of the start time, that is:

$$
\begin{align*}
    T_{j,\text{low}} &\leq t_3 \leq T_{j,\text{up}} \\
    T_{on,j} &= T_{on}
\end{align*}
$$

(5)

Where $t_3$ indicates the start time of transferable device $j$, $T_{j,\text{low}}$ and $T_{j,\text{up}}$ are the start time and the start time end respectively, $T_{on,j}$ and $T_{on}$ respectively indicate the maximum running time of the device $j$ during the run time and the actual running time of the device.

For the charging device, it is required to be fully charged during the user's predetermined period of time, and it’s also involved in battery capacity constraints, that is:

$$
\begin{align*}
    T_{on,i} &\geq T_{low} \\
    T_{off,i} &\leq T_{up} \\
    Cap_{pre,i} + \sum_{t=T_{on,i}}^{T_{off,i}} \eta_i X_{i,t} W_{i,t} &\leq Cap_i
\end{align*}
$$

(6)

Where $T_{on,i}$ and $T_{off,i}$ represent the start and end run times respectively, $T_{low}$ and $T_{up}$ denote the start charging time and the end charging time of the charging device respectively, $Cap_{pre,i}$ represents the initial charge of the charging device, $Cap_i$ is the battery capacity, $\eta_i$ is the charging efficiency of the device $i$, $X_{i,t}$ indicates whether the device $i$ is charging in the period of $t$, the value is 1 when it’s charged and the value is 0 when it’s uncharged, $W_{i,t}$ represents the charging efficiency of the device $i$ in the period of $t$. 


For the energy storage device, it’s subject to maximum and minimum charge and discharge limits:
\[ \alpha_{i,\text{min}} \leq \frac{\text{Cap}_i}{t} \leq \alpha_{i,\text{max}} \text{Cap}_i \] (7)

Where \( \text{Cap}_i \) is the energy stored by the energy storage device \( i \) in the period of \( t \), \( \alpha \) denotes the minimum and maximum charge and discharge degrees of the device \( i \) respectively.

If the user dissatisfaction and the peak valley difference can be measured by electricity tariff, the above-mentioned multi-objective optimization problem can be transformed into a single objective optimization problem by introducing the conversion factors \( \alpha \) and \( \beta \) respectively. The objective function becomes:
\[ \min F = C + \alpha U + \beta D + \omega S \] (8)

Where \( \omega \) is the penalty factor for the device, \( S \) is the penalty function value.

**IMPROVED GRAVITATIONAL SEARCH ALGORITHM**

**Gravitational Search Algorithm**

The gravitational force between particle \( i \) and particle \( j \) can be expressed as:
\[ F_{ij}^d(t) = G(t) \frac{M_i(t) \times M_j(t)}{R_{ij}(t)} \times (x_i^d(t) - x_j^d(t)) \] (9)

Where \( G(t) \) is universal gravitational constant in the period of \( t \), \( M_i(t) \) and \( M_j(t) \) indicate the inertial mass of the particles \( i \) and \( j \) respectively, \( R_{ij}(t) \) is the Euclidean distance between particle \( i \) and particle \( j \), \( \epsilon \) represents a very small constant, \( x_i^d(t) \) and \( x_j^d(t) \) are the positions of the particles \( i \) and the particles \( j \) in the d-dimensional space respectively.

In the period of \( t \), the gravitation and acceleration of the particle \( i \) in the d-dimensional space are as follows:
\[ F_i^d(t) = \sum_{j=1,j \neq i}^{N} \text{rand}_j \times F_{ij}^d(t) \] (10)
\[ a_i^d = \frac{F_i^d(t)}{M_i(t)} \] (11)

Where \( \text{rand}_j \) is a random number.

Particles will update the speed and position in each iteration according to the acceleration, that is:
\[ v_i^d(t+1) = \text{rand}_j \times v_i^d(t) + a_i^d(t) \] (12)
\[ x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \] (13)

**Improved Gravitational Search Algorithm**

The gravitational search algorithm has the advantages of simple structure, but there are premature convergence and poor precision in the optimization process. In view of these problems, it’s combined with the memory and group information sharing ability of Particle Swarm Optimization to update the speed of GSA, thereby the diversity of populations are increasing and the shortcomings of premature convergence are overcome. The bio-parasitic behavior mechanism is introduced into the GSA, the convergence rate and the search
precision are accelerated by the particles are exchanged between the parasite group and the host group and the co-evolution of the two populations. The population diversity and global search ability are improved by eliminating the less suitable particles and replacing the same number of particles with the reinitialize, which makes use of other algorithms to solve the problem that the search results are easy to fall into the local optimum in the process of building electricity scheduling.

MEMORY AND GROUP INFORMATION SHARING CAPABILITIES

When the velocity of the particle is updated, the formula of the GSA is updated by the equation (12). In the iteration process, the particle only updates the current search information, and the optimal solution information between the individual and the group is not retained. It can make up for this deficiency of the GSA by observing the speed updating formula (14) of the PSO, so that the GSA has the ability of remember and share information. The improved speed update equation is as follows (15).

\[ v_i^d(t + 1) = \omega v_i^d(t) + c_1 \text{rand}_1(p_{best} - x_i^d(t)) + c_2 \text{rand}_2(g_{best} - x_i^d(t)) \]  

(14)

\[ v_i^d(t + 1) = \text{rand}v_i^d(t) + c_1 \text{rand}(p_{best} - x_i^d(t)) + c_2 \text{rand}(g_{best} - x_i^d(t)) + a_i^d(t) \]  

(15)

Where \( v_i^d(t), a_i^d(t) \) and \( x_i^d(t) \) represent the velocity, acceleration, and position of particle \( i \) respectively in the period of \( t \), \( \omega \) is the inertia weight, \( \text{rand}, \text{rand}_1 \) and \( \text{rand}_2 \) all represent the random number between \([0,1]\), \( c_1 \) and \( c_2 \) are constant between \([0,1]\), \( p_{best} \) and \( g_{best} \) represent the particle \( i \) and the best position of all the particles in the group respectively.

In order to study the convergence behavior of the PSO algorithm, Clerc [8] introduced the compression factor \( \lambda \) in the velocity update of the algorithm in 2002. Therefore, the convergence behavior of the GSA algorithm can be studied by introducing the factor \( \lambda \), the velocity updating equation is as follows:

\[ v_i^d(t + 1) = \lambda(\text{rand}v_i^d(t) + c_1 \text{rand}(p_{best} - x_i^d(t)) + c_2 \text{rand}(g_{best} - x_i^d(t))) + a_i^d(t) \]  

(16)

Where compression factor is \( \lambda = \sqrt{2 - \Phi + \sqrt{\Phi^2 - 4\Phi}} \), generally, when \( \Phi = c_1 + c_2 = 4.1 \), that is \( \lambda = 0.729 \), the algorithm achieves a better convergence effect.

A DUAL-SPECIES GRAVITATION SEARCH ALGORITHM BASED ON BIOLOGICAL PARASITIC BEHAVIOR

This paper proposes a Parasitic [9] Behavior Gravitational Search Algorithm (PBGSA) based on biomechanical behavior on the basis of the above algorithm improvement, in which the particles in the population are divided into two groups: the parasitic population and the host group, and it corresponds to the number of particles were \( N_p \) and \( N_h \).

The velocity of the parasitic particles in PBGSA is updated according to equation (16), and the velocity of the host group particles is updated according to formula (17).

\[ v_i^d(t + 1) = \begin{cases} 
\lambda(\text{rand}v_i^d(t) + c_1 \text{rand}(p_{best} - x_i^d(t)) + c_2 \text{rand}(g_{best}^h - x_i^d(t))) \\
+ a_i^d(t), f(g_{best}^p) \geq f(g_{best}^h) \\
\lambda(\text{rand}v_i^d(t) + c_1 \text{rand}(p_{best} - x_i^d(t)) + c_2 \text{rand}(g_{best}^h - x_i^d(t))) \\
+ c_2 \text{rand}(g_{best}^h - x_i^d(t)) + a_i^d(t), f(g_{best}^p) < f(g_{best}^h) 
\end{cases} \]  

(17)

Where \( c_{11}, c_{21}, c_{12}, c_{22} \) and \( c_{23} \) are constant coefficients, \( \text{rand}_i \) is a random number between \([0,1]\), \( g_{best}^h \) and \( g_{best}^p \) are the optimal population of the host group and the parasite group respectively, \( f(g_{best}^h) \) and \( f(g_{best}^p) \) are the optimal individual fitness in the host group and the parasite group respectively.
The idea of the algorithm is that the parasitic population absorbs the nutrient from the host group at a certain number of iterations $K$, that is, the particles in the two populations are arranged in ascending order according to the degree of fitness. Since the minimum value is obtained in this paper, the first half small particles of fitness are divided into parasitic groups, and the second half of the particles are assigned to the host group. In the case of parasitic behavior, if the optimal particle in the host group is less than the optimal particle fitness in the parasite group, the particles in the host population evolve to the direction of individual optimal and parasitic population optimal; otherwise, the two populations are independently evolved. In addition, after the parasite absorbed the nutrition from the host group, the poor compatibility particles for 50% of the host group are eliminated, and re-initialized the same number of particles instead of its location, so as to maintain the size of the population integrity and improve diversity of population and speed up the convergence rate.

**ALGORITHM FLOW**

1. Initialize the velocity and position of the particles in the population, and set each parameter in the optimization process.
2. Calculate the fitness value $f_{i}$ of each particle in the population, and select the current optimal individual position $p_{best}$.
3. Each particle is sorted in accordance with the size of the fitness, a parasitic behavior is happened each interval K generation, that is, for the minimum optimization problem, particles with small fitness values are classified into the parasitic population, particles with large fitness values are classified into the host group.
4. Select respectively the optimal location of the parasite and the host group $g_{best}$ and $h_{best}$.
5. Eliminate the 50% individuals with poor fitness in the host group and replace them with the re-initialized number of particles.
6. Elite retention operations for the best individual in the population.
7. Calculate the gravitational constant $G(t)$ of each particle and the mass $M$ and the acceleration $a$ of the individual particles in the two populations.
8. According to Eq. (15) and (16), the velocity $v$ of the particles in each population is calculated and the particles are respectively moved accordingly.
9. The result is output if the end condition is satisfied, otherwise return to step (2).

**CASE STUDY**

**The Parameters Involved in the Model**

This article simulates the electricity schedule of four types of users for the building in one day, the 24h is divided into 96 time periods by time unit 15min. Real-time electricity price data [10] as shown in Figure1, the power generation device parameters refer to the literature [10], the uncontrollable device, the interruptible device, the transferable device, the charging device and the energy storage device parameters reference [7].
Simulation Results and Analysis

Compare the particle swarm optimization based on parasitic behavior (PBPSO) [11], the standard gravitational search algorithm (GSA), the improved gravitational search algorithm with memory and group information sharing (MGSA) and PBGSA proposed in this paper.

The parameters of the simulation are the same, that is, the population size is set to 80, the iteration is 3000 times, the number of optimization is 20; the conversion factor $\alpha$ in the objective function of the ordinary home users, office workers, commercial users and vacant users is 0.1, 0.2, 0.9 and 1 respectively, the value of $\beta$ is taken 1, the penalty factor $\omega$ is 100. The population size of the parasitic and host groups in the PBGSA is 40, the number of iterations $K = 20$, the learning factor $c_1 = c_2 = 0.05$ in the speed update formula of the equation (15), $c_1 = c_2 = 1.49$, $c_1 = c_2 = c_3 = 1.376$ in the equation (16), the inertia weight $\omega$ is 0.7298 in PBPSO, and the other parameters are the same as those in PBGSA, the learning factor $c_1 = c_2 = 0.05$ in MGSA.
The optimal scheduling results of the 20 optimal scheduling of PBGSA are selected. The four types of building users daily electricity situation before and after optimization shown in Figure 2, where the bar chart shows the device electricity situation, acupuncture chart shows the new energy power generation situation. The consumption of electricity for vacant users only from the line loss and can’t be controlled, so the electricity situation unchanged before and after optimization. It is possible to obtain the law by comparative graph analysis before and after the optimization of the scheduling. A part of electricity load transfer to the low price period after optimizing the scheduling. The battery charge and discharge and the characteristics of energy storage are fully utilized to ease the electricity peak tension, the peak value of power consumption is reduced after optimization, which reduces the user's total daily electricity and plays an important role in the smooth operation of the grid. According to compare with Figure 2 (a1) and (b1), the reduce of load power consumption and the increase of power generation surplus power after the optimization can be seen in the new energy generation period, so that excess electricity can be sold to the grid to obtain a certain economic benefits. Therefore, according to joint scheduling for the various habits of users, the degree of freedom of the equipment is increased, then there is a greater space to schedule electrical device and protect the building user's economy and comfort.

Table I shows the comparison of the daily total tariff, user dissatisfaction and total power consumption peak valley difference of all types of users before and after scheduling with PBGSA and MGSA. It can be seen from the data in Table I, the improved gravitational search algorithm in this paper is lower than the four categories of users of the indicators before the optimization, that is, the economy, comfort and stability are relatively good.
Table 1. Comparison of scheduling results.

<table>
<thead>
<tr>
<th>The style of users</th>
<th>Initial schedule</th>
<th>After optimization with PBGSA</th>
<th>After optimization with MGSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>The total electricity bill /yuan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The ordinary home users</td>
<td>7.65</td>
<td>4.70</td>
<td>4.71</td>
</tr>
<tr>
<td>The office workers</td>
<td>5.88</td>
<td>3.34</td>
<td>5.24</td>
</tr>
<tr>
<td>The commercial users</td>
<td>15.72</td>
<td>8.59</td>
<td>9.36</td>
</tr>
<tr>
<td>The vacant users</td>
<td>0.87</td>
<td>0.87</td>
<td>0.87</td>
</tr>
<tr>
<td>The user dissatisfaction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The ordinary home users</td>
<td>33.47</td>
<td>27.34</td>
<td>120.91</td>
</tr>
<tr>
<td>The office workers</td>
<td>18.52</td>
<td>5.95</td>
<td>13.01</td>
</tr>
<tr>
<td>The commercial users</td>
<td>219.01</td>
<td>210.61</td>
<td>214.67</td>
</tr>
<tr>
<td>The vacant users</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>The total peak valley difference /KW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The four categories of users</td>
<td>4.9</td>
<td>4.25</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Compared with the PBPSO, GSA and MGSA algorithms, the average optimization result is 20 times. The optimization process is shown in Figure 3. It can be seen from the figure that the improved gravitational search algorithm has the advantages of fast convergence, precariousness and good global search ability. From the comparison of the optimal objective function values and the average objective function values of the four optimization algorithms in Figure 4, the improved PBGSA algorithm is better.

![Figure 3. Comparison of four optimization algorithms’ optimization process algorithms’ value.](image1.png)

![Figure 4. Comparison of four optimization.](image2.png)

CONCLUSION

(1) The improved gravitational search algorithm proposed in this paper introduces the memory and population information sharing ability of the particle and the dual-group idea based on the biological behavior mechanism on the basis of GSA. Through the rule of synergetic and survival for the two communities, the lack of the original GSA is overcome, it’s of strong global search ability and better search accuracy.
(2) The improved gravitational search algorithm is used to optimize the building electricity scheduling model and obtain good results, which proves the practicability of the algorithm.

(3) With the increase for the number of building users, the scheduling space becomes larger and the optimization effect is better. Finally, the electricity consumption of each building is lower, the dissatisfaction is smaller, and the peak valley difference of the electricity consumption of the whole building is greatly reduced, it is also conducive to the peak shaving of the grid.

REFERENCES