Optimizing Microgrid Power Dispatch with Integrated Ground Source Heat Pumps Using Cellular Automata

Peng Wang
College of Electronic Information and Automation, Tianjin University of Science and Technology, 300222, China

Shunqi Yang
College of Electronic Information and Automation, Tianjin University of Science and Technology, 300222, China
E-mail: autowangpeng@tust.edu.cn, yangshunqitust@163.com

Abstract

As a new type of energy supply and management system, this paper improves a simulation method based on cellular automata (CA) to optimize power dispatching in microgrids, especially for the ground source heat pump (GHP) system. Firstly, this paper simulates the dynamic behavior and interaction of each unit in the microgrid using cellular automata, addressing uncertainties on both the supply and demand sides. Secondly, this paper uses a two-level optimization method to enhance the maximization of self-consumption and optimize energy flow in the grid. The results show that this method can effectively improve microgrid energy utilization efficiency, reduce operating costs, and enhance system reliability and resilience.

Keywords: Microgrid, Cellular automata, Power dispatching, Sustainable energy sharing, Ground source heat pump

1. Introduction

With the growth of global energy demand and the emphasis on environmental protection, the traditional centralized energy supply mode faces the challenges of large energy transmission loss and high carbon emissions. As a distributed energy solution, microgrid has attracted much attention, which can integrate renewable energy, improve supply reliability and flexibility, and reduce transmission loss.

Ground source heat pump is the key heating and cooling equipment of microgrid. It uses shallow geothermal resources to save energy efficiently, reduce carbon emissions, and significantly reduce electricity consumption in summer and winter. In autumn, solar panels store excess power to the battery, and supply power during the peak power consumption in winter to ensure demand. When electricity is surplus, it can also supply neighbors and realize power allocation and sharing.

However, when the ground source heat pump is integrated into the microgrid, its power consumption fluctuation and collaborative work problems bring new challenges to power scheduling [1]. Cellular automata can accurately capture the dynamic interaction of components through modeling analysis and realize power scheduling optimization, which is of great significance for improving the reliability of microgrid, reducing costs and promoting sustainable energy development.

The rest of this article is organized as follows. The second section introduces the three key equipment used in the system. In the third part, the cellular automata model is used to model the neighborhood power exchange system. In the fourth part, a single house is taken as an example to analyze and calculate the propagation probability between cellular automata, and the specific modeling analysis is carried out. The fifth part summarizes the main content of this paper.

2. Key Technology Introduction

The micro-grid is composed of multiple buildings composed of such buildings, which are equipped with photovoltaic solar panels, ground source heat pump technology and energy storage batteries, as shown in Fig.1. The following is an introduction to these three technologies.

Fig.1 House schematic diagram

2.1. Photovoltaic solar power generation technology

Monocrystalline silicon solar panels are laid on the roof of a 200 square meter house and the wall with the best orientation. The inclination angle is determined according to the latitude to fit the solar radiation angle and improve the capture efficiency.

The installed power (P_{total}) is given by the following formula:

$$P_{total} = n \times P_s \tag{1}$$

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The n represents the number of photovoltaic solar panels, and P_s represents a single power.

Through the photovoltaic effect, the solar energy is converted into direct current, and the inverter (conversion efficiency (η_{inv}) is about 95 % -98 %) is converted into alternating current for use in the house. The power generation P_{pv} (t) fluctuates in real time with the sunshine intensity I(t) and temperature T(t), following the formula:

$$P_{pv}(t)=P_{total}\times\frac{I(t)}{I_{STC}}\times\left[1+\partial\times(T(t)-T_{STC})\right] \tag{2}$$

I_{STC} is the standard test light intensity (1000W / m2), T_{STC} is the standard test temperature (25℃), and ɑ is the power temperature coefficient (about-0.4%/℃ for monocrystalline silicon)[2].According to the meteorological data, the power generation is calculated hourly and the power generation curve is constructed as shown in Fig.2.

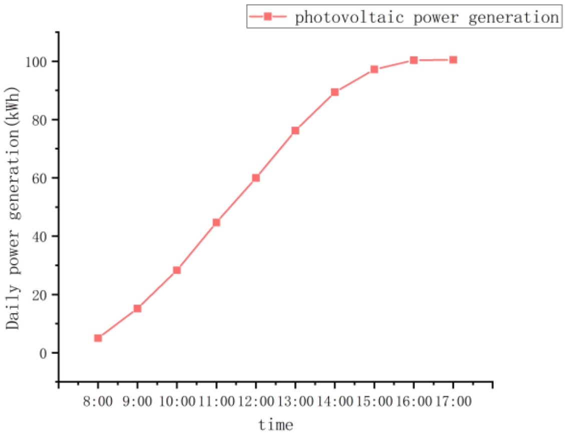

Fig.2 Solar panel daily power generation curve

2.2. Ground source heat pump

The ground source heat pump uses the principle of Carnot cycle and inverse Carnot cycle to transfer cold and heat. In winter, the heat pump unit absorbs the heat in the soil through the underground buried pipe system, and transmits the heat to the room through the heat exchanger to achieve heating. In summer, the heat pump unit releases the indoor heat into the soil through the underground buried pipe system to achieve refrigeration. At the same time, the ground source heat pump also utilizes the huge heat storage capacity of the underground soil to form an annual cold and heat cycle. The schematic diagram of ground source heat pump is shown in Fig.3.

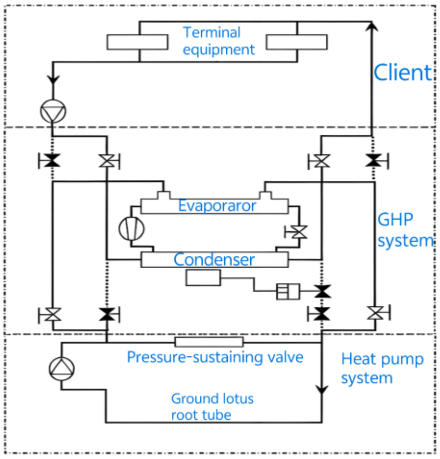

Fig.3 Ground source heat pump schematic diagram

The main power consumption of ground source heat pump is compressor operation, heat exchanger operation and waterway circulation.

The heating performance coefficient of ground source heat pump can be expressed as:

$$\beta=\frac{Q_h}{W}=\frac{(Q_e+W)}{W}=\frac{Q_e}{W}+1 \tag{3}$$

Among them, Q_h represents the heat provided by the heat pump system to the user,W represents the electrical energy consumed by the system, and Q_e represents the heat absorbed from low-temperature heat sources (such as water). The heating performance coefficient β is always greater than 1, which indicates that the geothermal heat pump heating can save high grade energy compared with the geothermal heat pump driven energy direct heating.

2.3. Battery energy storage system

The lithium-ion battery pack is selected, and the capacity is estimated based on the surplus electricity in spring and autumn and the deficit electricity in summer and winter. Battery rated capacity C_{bat} (unit is kWh). The voltage V_{bat}, the state of charge SOC(t) characterizes the proportion of remaining electricity, the update formula is:

$$SOC(t)=SOC(t-1)+\frac{\eta_c\times P_c(t)}{C_{bat}}-\frac{P_d}{\eta_d\times C_{bat}} \tag{4}$$

The η_c and η_d are the charge-discharge efficiency (charge about 93 % -95 %, discharge about 92 % -94 %), and the charge-discharge power. In the spring and autumn, when the solar power surplus, according to the control strategy to the appropriate current and voltage charging ; in summer and winter, the peak discharge of electricity is used to supplement energy, stabilize load fluctuations, and ensure continuous power supply.The lithium electronic battery is used to store the power, and the charge and discharge efficiency and self-discharge efficiency of the battery are calculated by the formula.

$$Round-TripEfficiency=\left(\frac{Discharged\ Energy}{Charged\ Energy}\right)\times 100\% \tag{5}$$

$$Self-Discharge\ Rate=\left(\frac{Initial\,Capacity-Final\,Capacity}{Initial\,Capacity}\right)\times 100\% \tag{6}$$

3. Model Construction

The second - order five - state probabilistic cellular automata model is used to conduct in - depth modeling and analysis for a specific case, that is, a scene composed of a single 200 square meters of housing buildings. In this model, the house integrated with ground source heat pump and solar photovoltaic power generation technology is treated as an independent producer - retailer unit, and a self - sufficient energy sharing system is constructed for each such unit[3]. This structure is named ' smart node ' by us, which can achieve power supply stability by intelligently adjusting the upper and lower limits of battery energy storage capacity as shown in Fig. 4.

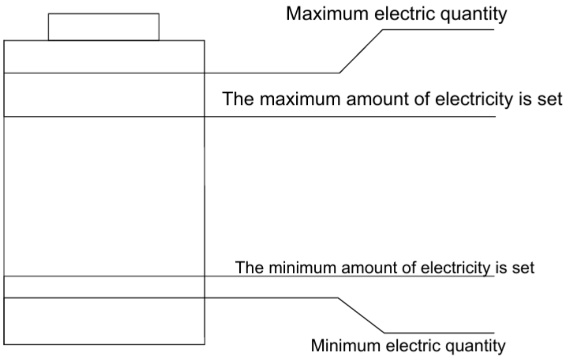

Fig.4 Battery power setting

3.1. Calculation of electricity generated and consumed by users

Statistics are made on the power generation of photovoltaic solar panels and the power consumption of ground source heat pumps as the main power consumption of pilot houses from 2021 to 2023, as shown in Fig. 5 and Fig. 6.

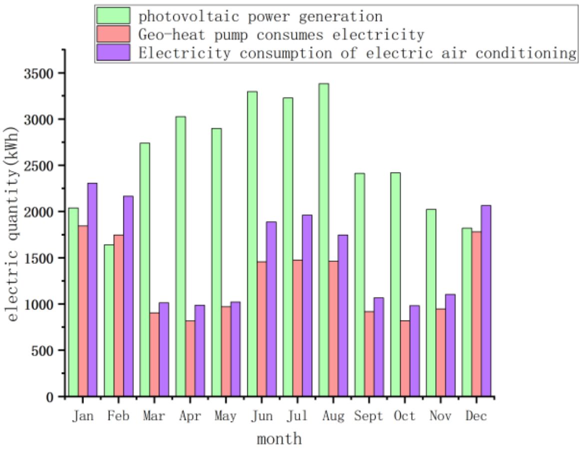

Fig.5 Monthly electricity consumption statistics

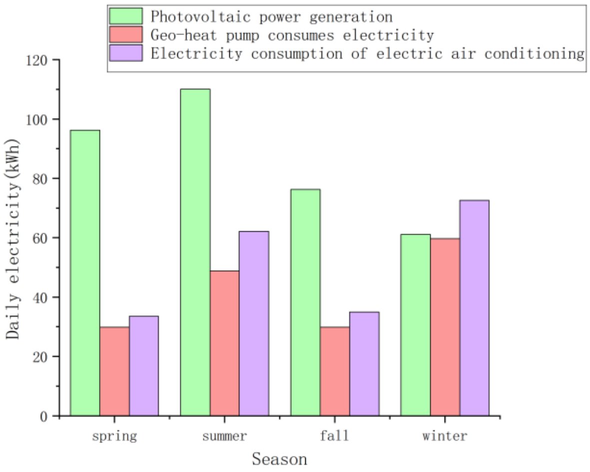

Fig.6 Seasonal electricity consumption statistics

It can be seen that the power consumption is significantly higher than the production period, which is concentrated in winter, so the cellular automata model is constructed in winter as an example.

3.2. Construction of cellular automata model

In our power system, we have built a microgrid architecture that consists of a number of interconnected components that can exchange energy. These components can be either pure electricity consumers or prosumers with both consumption and production capacity, and they usually represent residential user units [4]. These users are equipped with distributed power generation facilities, such as photovoltaic solar panels. Under this framework, energy consumers and prosumers are orderly arranged in a two-dimensional grid, which together constitute the basic unit of this complex and efficient energy network.

The cell space is expressed as

$$L=\{C_{ij};i,j\in 1,2...,n\ and\ j=1,2...,m\} \tag{7}$$

where n and m are the number of nodal elements along the vertical axis and the horizontal axis, respectively.

All building buildings are connected to neighbors through physical and information layers. Each house unit is used as a node to link to its own index (i, j) in the community virtual grid. The cellular automata model adopts Moore neighborhood as Fig.7, and the neighborhood equation is:

$$N(c_{ij})=\{c_{kl};|k-i|\le R,|l-j|\le R\},c_{ij}\in L \qquad (8)$$

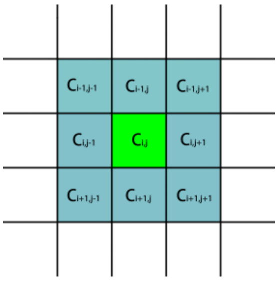

Fig.7 Moore neighborhood

Five cell states are set, and the state transition rules are shown in Fig.8.

State 1 : Solar energy can meet its own needs and charge the battery.

State 2 : Photovoltaic solar power generation can not meet its own needs, and the storage capacity of the battery can not meet its own needs. For the disadvantage state.

State 3 : The power generated by the photovoltaic solar panel can meet its own power demand and will be stored more than the power. Power supply state for neighbors.

State 4 : Power outage status.

State 5 : The state of power supply to the power grid.

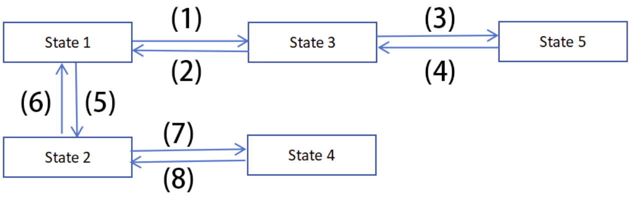

Fig.8 State transition diagram

(1) After three iterations of state 1, it is converted to state 3. That is, after a period of charging, the storage capacity of the battery is higher than the set maximum value ;

(2) The number of neighbors in the surrounding state 2 is n2, and the probability of n_2p_2 is converted to state 1. That is, when there is a state of lack of electricity around, the state of lack of electricity 2 is converted into a charging state 1 after power supply ;

(3) When $n_2 = 0$ and there is no state 2 around, it is converted to state 5 after three iterations. That is, when there is no neighbor in the state of power shortage, it will continue to be in the state of power supply to the neighbor, and after a certain period of time, it will be converted into a state of power supply to the power grid ;

(4) State 5 after an iteration, it is converted to state 3. That is, after supplying power to the grid, it is converted into state 3 ;

(5) When the solar power generation is lower than its own power consumption, the charging state 1 will be converted to the power shortage state 2 with the probability of P_3 ;

(6) n_1 is the number of state 3 that can be powered to neighbors. When power is supplied to state 2, state 3 is transformed into state 1 with the probability of n_1p_1 ;

(7) n_1 is the number of surrounding states 3, and the probability of $p_5 = p_4 / n_1$ is converted to state 4. That is to say, the smaller the number of surrounding power supply states 3, the greater the probability of power shortage state 2 transforming into power outage state 4 ;

(8) After the power supply of the power grid, it is converted into state 2 after 2 iterations ;

Under the micro-grid combined with ground source heat pump system.The simulation results are shown in Fig.9 when the battery power is not set. When the battery power is set, the simulation results are shown in Fig.10.

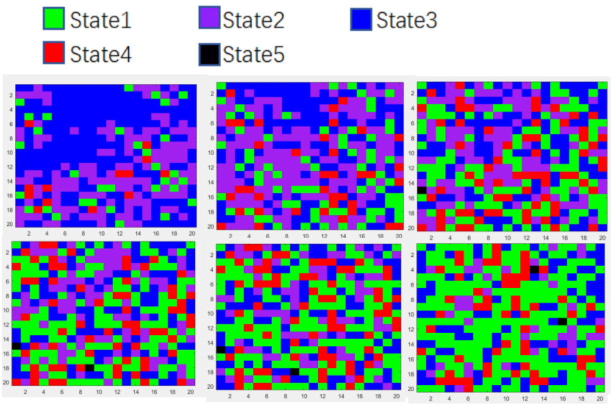

Fig.9 Simulation without setting the battery power

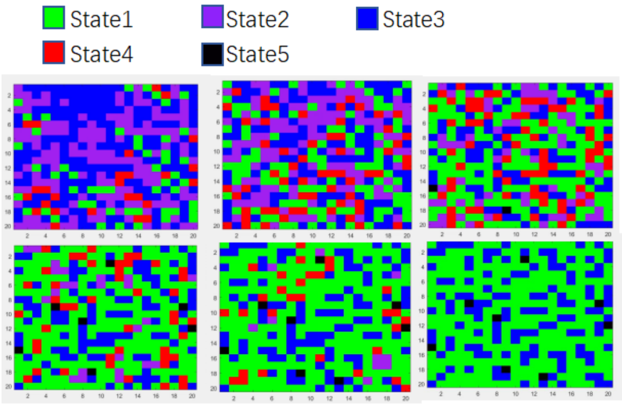

Fig.10 Simulation after the battery power setting

It can be seen from Fig.9 that when there is no electricity setting, at the end of the day, the number of power-deficient users is 47, an increase of 11.75 % compared to Fig.10. It can be seen that in winter days, the user 's power consumption state in the microgrid system is converted from an unstable state without the battery power setting to a stable state with the battery power setting ,the power setting of the battery can effectively improve the power stability of the user group.

4. Conclusion

This study explores and implements a two-level optimal storage strategy for battery power, explores the excellent low energy consumption and low carbon emission characteristics of ground source heat pump compared with electric heating system, and skillfully realizes the precise regulation and balance of power demand in summer and winter, that is, peak shaving and valley filling effect.On this basis, we introduce the cellular automata theory and construct an advanced model of microgrid energy sharing.

The technical scheme not only shows high popularization and application potential, but also can achieve efficient and intelligent configuration of energy while greatly reducing carbon emissions. Moreover, it can significantly reduce the dependence on the main power grid during the summer peak period, and has the ability to reverse power supply to the main power grid, thus effectively alleviating the operating pressure of the main power grid during the summer peak period and improving the stability and reliability of the entire power system.

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Authors Introduction

Ms. Peng Wang

She is a postgraduate tutor of Tianjin University of Science and Technology. In 2014, she received a doctorate from North China Electric Power University. The research direction is the functional safety assessment of safety instrumented systems.

Mr. Shunqi Yang

He received his Bachelor's degree in 2023 from the School of Electronic Information and Automation, Tianjin University of Science and Technology. Currently, he is a master's student at the same university. His research area is microgrid reliability.