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Case Study on the Application of Game Theory in Virtual Power Plants in Shanghai

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Abstract: This paper is a case study about virtual power plants in Shanghai. In this paper, the background of forming virtual power plants in China was analyzed first. Next, it is about the current situation of China's electricity market. Afterward, game theory was applied to form a model between consumers and the plant owners. At last, the paper analyzed the reasons why virtual power plants in Shanghai still have quite a few problems in comparison with those in South Australia. Through the analysis of the different development statuses of virtual power plants in Shanghai and South Australia, it can be seen that the development of virtual power plants in China still has a long way to go, and great efforts need to be made in terms of technical support and exploration of customers. The meaning of this whole paper is that it could raise the awareness of society and the government to pay more attention to the development of virtual power plants in Shanghai. Hopefully, many other cities will soon start the construction of their local virtual power plants and thus contribute to saving electricity in the future.

Keywords: Game theory, virtual power plant, payoff function

1. Introduction

Summer ushered in the peak of electricity consumption, prompting companies to request users to buy electricity or reduce usage to balance the peak and valley values. Whether individuals are willing to give up their surplus electricity in exchange for money and how the power company entices individuals to give up their electricity is a game.

China consumes a significant amount of electricity every year. By the end of December 2022, the cumulative installed capacity of power generation in the country was about 2.56 billion kilowatts, a year-on-year increase of 7.8%. Thermal power accounts for about 52% of the installed capacity [1].

Thermal power does satisfy the need for electricity. However, it not only consumes energy but also increases carbon emissions. The existing carbon capture and storage technology is yet immature, so thermal power is not a good choice. Subject to limited resources, uneven power generation, and a large impact on ecological protection, the large-scale growth space of hydropower is limited. Nuclear power has high safety constraints and limited site options. The only option we have seems to be new energy. According to CEC, the proportion of wind and photovoltaic power in the country will reach 65% under the carbon neutrality scenario in 2060 [2].

The randomness of the power generation side and the increase of peak-valley difference on the load side are difficult problems to solve, as the overall reliable capacity of the grid system is insufficient, and the future of long-cycle power storage technology is unclear. Nevertheless, as the number of new power system players, such as electric vehicles, has proliferated, the traditional demand side could output electricity to the grid.

Virtual power plants can greatly improve power load resiliency and help carry out construction adjustable industry, air conditioning, big data center load, and user-side energy storage [3]. Virtual power plants have been built and used for a long time in many countries. Shanghai, as one of China's very first cities to construct virtual power plants, is now moving towards constant exploration [4]. This article will analyze the characteristics of the Shanghai Power Grid and how game theory is applied in a virtual power plant in Shanghai.

2. Current Situation

China's electricity market is still in its infancy, so in the early days of constructing power plants in Shanghai, it was mainly based on the invitation system. However, with the introduction of relevant policies, the construction of the electricity market has begun to take shape, and Shanghai's virtual power plants are also moving towards independent trading [5]. In the sub-electricity consumption data of buildings in Shanghai, the total electricity consumption of air conditioning equipment and lighting electrical equipment accounts for over 70% [6]. The average load density in Shanghai is 2.8 times that of Beijing, but the annual average number of hours exceeding 95% of the maximum load of the year is only 36 hours, and the annual average of more than 97% is only 9 hours. To meet the peak in 2022, Shanghai will sweep the goods in the inter-provincial spot regardless of the cost, and the cost of adjusting the peak will be as high as 10 yuan/kWh, and there will be 2.8 billion yuan to be channeled. For Shanghai, relying on traditional methods to meet electricity demand is neither physically feasible nor economically friendly.

On December 5, 2019, China’s first provincial-level virtual power plant operation system was organized in Shanghai. Until 2022, Shanghai has organized 12 market-oriented transactions of virtual power plants and provided incentives of about 700,000 yuan for virtual power plants [7]. 226 customers participated in the transaction, with a total participation capacity of 87,000 kilowatts.

3. Analysis

In this scenario, the players are the electric power company, the government, and the electricity users. The users include those who output electricity into the grid and those who cut down the usage of electricity, yet both lower the load of the grid, so they could be seen as 1 category in this simplified model. However, as electricity companies are all state-owned in China, the government and company can be seen as 1 player. Therefore, the set of players are l={companies, users}

For actions, companies could decide the amount of money they have to pay to the users to buy electricity from them, and users decide the amount of energy they are willing to give to the grid or the amount of energy they are willing to save. The government can give out subsidies to increase the payoff of companies or users to encourage them to take part in the virtual powerplant, whereas actions of companies paying the consumers could be anything between 0 ~1. Users can decide the amount of electricity they want to output to the grid and the amount they output can also be anything between 0 and1.

For preference:

Let

p be the payment rate from companies to users, which ranges between 0 and 1.

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e be the amount of electricity the users decide to save or output back into the grid, also ranging between 0 and 1.

s be the subsidies provided by the government to the companies.

3.1. Company Payoff Function

The company wants to minimize costs while ensuring enough users participate. Their payoff decreases as p increases but may increase with subsidies s. A quadratic function could represent this preference.

$$Payoff_{company}(p) = -a - b \cdot p + c \cdot p^2 + s \ldots \quad (1)$$

Where a, b, and c are positive constants that shape the curve.

The term a-bp captures the decreasing payoff as the payment rate increases, while cp2 ensures that as p approaches 1, the cost for the company becomes very high. s directly adds to the company's payoff, representing the subsidy.

3.2. User Payoff Function

For users, the payoff initially increases with electricity savings or contributions but then decreases due to increasing discomfort or inconvenience. This can also be represented with a quadratic function.

$$\mathrm{Payoff}_{\mathrm{user}}(\mathrm{e}) = \mathrm{d} \cdot \mathrm{e} - \mathrm{f} \cdot \mathrm{e}^2 \ldots \quad (2)$$

Where d and f are positive constants.

The term d·e represents the increasing payoff for users as they contribute more, and -f·e2captures the decreasing payoff as contributions become too high.

3.3. Total System Payoff Function

The total system payoff is simply the sum of two individual payoff

$$\mathrm{Payoff}_{\mathrm{total}}(\mathrm{p}, \mathrm{e}) = \mathrm{a} - \mathrm{b} \cdot \mathrm{p} + \mathrm{c} \cdot \mathrm{p}^2 + \mathrm{s} + \mathrm{d} \cdot \mathrm{e} - \mathrm{f} \cdot \mathrm{e}^2 \ldots \quad (3)$$

This function captures the dynamics of both the company and user preferences in the system. Finding the maximum of this function can give the optimal strategies for both players. Even at its current scale, the actual performance of Shanghai's virtual power plant is far from ideal. In contrast, With the support of the South Australian Government, Tesla and electricity retailer Energy Locals are developing South Australia's Virtual Power Plant, which is a network of potentially 50,000 solar and Tesla Powerwall home battery systems across South Australia, forming the world's largest VPP. Tesla's virtual power plant in Australia was launched in 2017, and a pilot project has been conducted in South Australia. The pilot project was so successful that Tesla expanded its virtual plant to other Australian states, including New South Wales, Victoria, and Queensland. As of March 2023, more than 10,000 households participated in Tesla's virtual power plant in Australia. It helped reduce peak demand by more than 100 megawatts [8,9].

There is a huge difference between the two similar projects, and it is clear that the key reason that is preventing shanghai from forming a virtual powerplant that is reaching its ideal form is the lack of freely traded markets. Shanghai's virtual power plants are still invited, not market-based, and not cross-spatial autonomous dispatch, which greatly limits enterprises from entering. Plus, the lack of incentive payment made it almost impossible for the supply side to attract customers to join the virtual power plant, as the proceeds of joining are rather unattractive.

Electricity users in Shanghai are primarily office buildings and the like. The output equipment is not standardized, leading to high transformation costs, amounting to 0.8 billion. The power company is state-owned, and its priority is to ensure uninterrupted power supply. For office buildings, the marginal benefit of reducing peak power usage is low and might even be negative. The money they receive from the grid cannot cover their operating costs, mainly because equipment transformation takes up a significant portion. Still, it might upset customers, that can bring in revenue. The reason is that the government subsidies are mostly spent on purchasing electricity, rather than retrofitting or building new equipment to expand the coverage of the virtual power grid. Currently, only 226 customers joined. In South Australia, power companies operate in a free-competitive market, so ensuring a stable power supply is not their primary goal. Power outages for users might occur. Tesla's virtual power grid with solar energy storage pillars can be seen as an investment to offset losses during power outages. These storage pillars are standardized, and the cost of integrating them into the virtual grid, ensuring parameters like frequency change, voltage change, and response time meet requirements, is relatively low. Therefore, users can receive more subsidies. Power companies are also willing to do this because their electricity supply costs are lower than building additional storage or power plants. Moreover, the government can increase public satisfaction and support rates through this method. It benefits all parties involved, so the virtual power plant has been promoted in South Australia [10].

4. Conclusion

In conclusion, through the analysis of the different development statuses of virtual power plants in Shanghai and South Australia, it can be seen that the development of virtual power plants in China still has a long way to go, and great efforts need to be made in terms of technical support and exploration of customers. Fortunately, a lot can be learned through the practice of South Australia and other regions with mature development of virtual power plants. It is believed that China's virtual power plants will develop more and more prosperous in the future, which can save more energy for China and help the development of industry.

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