Research on Cold Storage Multi-objective Optimal Operation with Photovoltaic Power Generation

Bo Hu[1], Tao Wang[1], Penghui Li[1], Fei Qu[1], Chaonan Ji[1], Liang Kong[2], Heng Du[1], and Haiyang Wang[1]
[1] State Grid Huludao Electric Power Supply Company, Huludao, China
[2] Northeastern University, Shenyang, China
Email: {dianlihubo, ququ1940}@sina.com, {lndywt, lnlipenghui, k_liang1993}@163.com, {1134616487, 657225576}@qq.com, duheng@tju.edu.cn

***Abstract*—As the total amount of cold storage increasing year by year, the disorderly access of heavy power load will make the power grid peak and valley difference increase. At the same time, the high operating cost will also increase the burden of users, so the optimal operation of the cold storage is crucial. Based on the TOU price policy, the optimal operation model of cold storage is established with the objective function of minimizing the operating cost and the load power variance. The optimal operation strategy of cold storage is solved by membership function and particle swarm algorithm, and the load and start of cold storage are calculated according to the 0-1 knapsack algorithm. The influence of different price on the operation strategy is analyzed. Making a garlic market in Henan as example analysis, shows the results that considering the PV and TOU case, optimal control strategy to reduce operating costs and power grid peak valley difference has obvious advantages, in which the cost saving rate in cold season and boom season are 199.4% and 92.6% respectively.**

***Index Terms*—cold storage, operating costs, load variance, particle swarm optimization**

I. Introduction

In recent years, with the improvement of people's living standard, the cold storage industry has developed rapidly, at the end of 2015, China's total cold storage reached 26 million 260 thousand tons, compared with 2014, an increase of 28% [1]. At the same time, the cold energy consumption is also increasing year by year, according to the research shows that the maximum energy consumption per unit of refrigerated storage for the minimum energy consumption more than 5 times, visible under the same conditions, index of energy consumption per unit product varies greatly, there is great potential in energy saving of cold storage [2]

The implementation of peak and valley price policy in our country can guide users to save energy, at the same time it can achieve peak clipping and valley filling and improve the stability of power grid. The literature of [3] and [4] mainly through the infrared nondestructive testing technology to make up for the cold storage insulation defects and put forward new insulation measures, in order to achieve the purpose of energy saving cold storage operation. The literature of [5] mainly through the finite difference method to proceed numerical simulation for based on the unsteady heat transfer model, obtain the using extruded vinyl foam has excellent thermal insulation performance. The literature of [6] through the numerical simulation and parameter optimization of the cold air curtain performance provides the optimal settings for the air velocity and position of the air curtain. From above the main structure of the cold storage problem, when the cold storage with photovoltaic power generation, photovoltaic grid connected policy, the flat price of peak and valley and subsidy policy and other issues, reduce the operation cost of cold storage has become an urgent need to consider the issue. The literature of [7] is mainly from the consideration of the CCHP system with photovoltaic cooling, to establish economic optimization model. In general, the researchers mainly consider the energy saving from the cold storage structure and the CCHP system, but seldom consider the optimization strategy of the cold storage with photovoltaic power generation under the environment of time-sharing electricity price.

In this paper, based on time-of-use (TOU) price policy, to study on the optimal operation strategy of cold storage system with photovoltaic power generation system, with the operating cost of the cold storage and the fluctuation of the grid load as objective function to establishment of cold storage operation control model, the membership function of fuzzy mathematics and particle swarm optimization algorithm are used to solve the problem, and according to the 0-1 knapsack algorithm, the control of the specific load is obtained. The effectiveness of the optimization model is verified by an example of a garlic trading market in Henan, and the operation strategy of cold storage under different electricity price is compared.

II. Optimization Model of Cold Storage System with PV Generation

A. System Structure

In this paper, the cold storage system with photovoltaic power generation system is taken as the research object, the system is composed of photovoltaic power generation

Manuscript received May 30, 2017; revised November 3, 2017.

doi: 10.18178/ijoee.5.2.101-105

module, storage battery, grid connected inverter, bi-directional inverter, central control unit, AC power distribution equipment, various kinds of load of and monitoring system, the schematic diagram of the system is shown in Fig. 1.

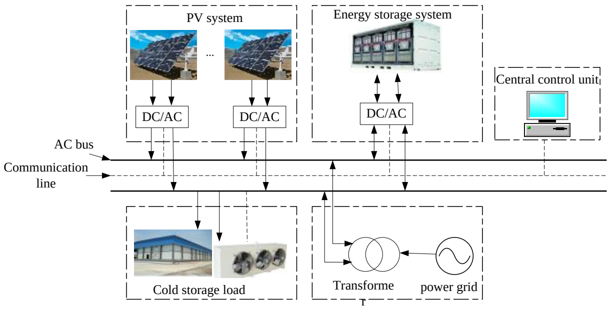

Figure 1. Cold storage system structure with PV generation.

The primary purpose of photovoltaic power generation system is to meet the demand of cold storage compressor and ammonia pump, when the generating capacity exceeds the cold storage load demand, the battery can be charged (through the battery charging state to determine whether charging) or grid; when the generating capacity is insufficient, the power supply is supplied by the storage battery (judge whether the discharge can be obtained) or the electricity is purchased from the large power grid.

B. Objective Function

Optimization model of cold storage based on photovoltaic generation system, establishing the minimum objective function of operating cost and power grid load fluctuation. In order to meet the cold storage temperature, the optimization principle mainly includes two aspects: 1) In the case of TOU price, considering the economy of the user, the minimum operating cost of the system is taken as the objective function. 2) When the cold storage is used to optimize the operation mode, it is possible to form a new peak load, which is caused by the large load power of the cold storage, and bring up the peak valley difference; At the same time, the more stable the load change, the less the reserve capacity of the generator set and the loss of the power system network, taking the minimum variance of load as the objective function.

Objective function (1): The operating cost f_1 of the cold storage is minimal, its include: electricity purchase cost to large electricity $C_s(t_i)$, operating cost of photovoltaic power generation system $C_{PV}(t_i)$, operating cost of energy storage system $C_{Bt}(t_i)$, earned income of selling electricity to large power grid $I_{an}(t_i)$, and government subsidies $I_{sub}(t_i)$.

$$\min\ f_1 = C_s(t_i) + C_{PV}(t_i) + C_{Bt}(t_i) - I_{an}(t_i) - I_{sub}(t_i) \quad (1)$$

where: $C_s(t_i) = \sum_{i=0}^{n} J_s(t_i) P_s(t_i)$;

$C_{PV}(t_i) = \sum_{i=0}^{n} J_{PV}(t_i) P_{PV}(t_i)$; $C_{Bt}(t_i) = \sum_{i=0}^{n} J_{Bt}(t_i) \left| P_{Bt}(t_i) \right|$; $I_{an}(t_i) = \sum_{i=0}^{n} J_{an}(t_i) P_{net}(t_i)$; $I_{sub}(t_i) = \sum_{i=0}^{n} J_{sub}(t_i) P_{PV}(t_i)$; $J_s(t_i)$ for t_i time from the purchase price of large power grid; $J_{PV}(t_i)$ for t_i time cold storage load from large power network shopping power; $J_{PV}(t_i)$ is the power generation of photovoltaic array for t_i time; $J_{Bt}(t_i)$ is the maintenance costs for battery units; $P_{Bt}(t_i)$ for t_i time battery charging power, discharge is positive, charge is negative; $J_{an}(t_i)$ for the unit price of electricity; $P_{net}(t_i)$ for t_i time grid connected power; $J_{sub}(t_i)$ for government subsidies electricity price.

Objective function (2): The average variance of power load is the smallest have these:

$$\min\ f_2 = \sum_{i=1}^{24} (P_L(t_i) + \sum_{i=1}^{n} P_{sj}(t_i) - P_{av})^2 \quad (2)$$

$$P_{av} = \sum_{j=1}^{n} (P_L(t_i) - \sum_{i=1}^{n} P_{sj}(t_i)) / 24) \quad (3)$$

where: $P_L(t_i)$ for power grid t_i time load power value; $P_{sj}(t_i)$ for cold storage j at t_i moment from the big electricity purchase electricity value; P_{av} is the average daily of load power.

To sum up, the objective function of the optimal operation of the cold storage system with photovoltaic power generation system:

$$\min\ f = \{ f_1, f_2 \} \quad (4)$$

C. Constraint Conditions

The constraints of the PV system including the power balance constraints, the battery operation constraints, the switching power constraints from large power grid and load characteristics constraints.

1) Power balance constraint

When charging, there is:

$$P_s(t_i) + P_{PV}(t_i)\eta_{PV} + \frac{P_{Bt}(t_i)}{\eta_{Bt}} - P_{net}(t_i) - P(t_i) = 0 \quad (5)$$

When discharging, there is:

$$P_s(t_i) + P_{PV}(t_i)\eta_{PV} + P_{Bt}(t_i)\lambda_{Bt} - P_{net}(t_i) - P(t_i) = 0 \quad (6)$$

where: η_{PV} for photovoltaic power generation efficiency; η_{Bt} for battery charging efficiency; λ_{Bt} for battery discharge efficiency; $P(t_i)$ is the total load power of cold storage.

2) Battery operation constraints

$$P_{ch}^{\max}(t_i) \le P_{Bt}(t_i) \le P_{dis}^{\max}(t_i) \quad (7)$$

$$C_{soc}^{\min} \le C_{soc}(t_i) \le C_{soc}^{\max} \quad (8)$$

$$\sum_{i=0}^{n} P_{Bt}(t_i)\Delta t = 0 \quad (9)$$

where: $P_{ch}^{\max}(t_i)$ and $P_{dis}^{\max}(t_i)$ are respectively the maximum power of battery charge and discharge; $C_{soc}^{\min}$ and $C_{soc}^{\max}$ are the minimum and maximum capacity of the battery operation; Formula (9) indicates that the battery is in operation, the state of charge and discharge by the same.

3) Switching power constraints from large power grid.

$$0 \le P_s(t_i) \le P(t_i)^{\max} \tag{10}$$

$$0 \le P_{net}(t_i) \le P_{PV}(t_i) \tag{11}$$

where: $P(t_i)^{\max}$ is the maximum power value from the power grid, that is, the maximum power load.

4) Cooling load and general load

In order to ensure the cold storage temperature to meet the requirements of the working conditions, the apparatus for generating cold quantity in cold storage is called the cooling load [8]. The cooling capacity of the refrigerating load to meet the temperature requirements of the refrigerator, However, Different refrigerated items corresponding to different temperature section, for example, the optimal temperature of garlic refrigeration is -3℃~1℃. At the same time, cold storage as energy storage load, in order to make the target optimal, can be considered in peacetime and off-peak time cooling capacity, these is:

$$P_{\text{cool}}^{\min}(t_i) \le P_{\text{cool}}(t_i) \le P_{\text{cool}}^{\max}(t_i) \tag{12}$$

where: $P_{\text{cool}}(t_i) = \dfrac{\sum_{j=1}^{k} P_j(t_i)}{\eta} = \dfrac{\sum_{j=1}^{k} \rho C_p \varepsilon \alpha V_j \Delta T_{ij}}{\eta}$; $P_{\text{cool}}^{\min}(t_i)$ and $P_{\text{cool}}^{\max}(t_i)$ for the power range of $P_{\text{cool}}(t_i)$ in the temperature range; $P_j(t_i)$ is the power required for the j storage room in the cold storage for t_i; ρ is the cold storage air density; C_p is the constant pressure specific heat for air; V_j is the actual volume of the j cold storage room; ΔT_{ij} is the difference between the target temperature and the ambient temperature; ε for the cold storage chamber insulation performance; α is the volume utilization rate of cold storage room, considering the effect of cold storage cold storage machine stroke not available space; η is the efficiency of cooling capacity for refrigeration equipment, The refrigeration efficiency obtained by cooling capacity and power consumption of the early.

The common load due to switching power is a certain value, then

$$P_{norm}(t_i)^{\min} \le P_{norm}(t_i) \le P_{norm}(t_i)^{\max} \tag{13}$$

where: $P_{norm}(t_i)$ is the power value of the normal load at t_i time, $P_{norm}(t_i)^{\min}$ and $P_{norm}(t_i)^{\max}$ for general load at t_i moment power range.

5) Indirect energy storage load constraint

Direct storage load said photovoltaic battery in cold storage and other storage load, according to the price system and other control information storage and release energy ,for direct storage load constraint have formula (5)~(9). While the indirect storage load is freezer compressor and ammonia pump and refrigeration equipment in cold storage , the power into the cold, need to meet the minimum amount of cold storage refrigeration and cooling load maximum power value (12), but also need to meet the power balance, these is

$$P_{\text{cool}}(t_i) = f(P_{PV}(t_i), P(t_i)) \tag{14}$$

where: $P_{\text{cool}}(t_i) = f(P_{PV}(t_i), P(t_i))$ is indirect energy storage load power balance equation.

D. Power of Photovoltaic Power Generation

Photovoltaic power generation $P_{PV}(t_i)$ power value, Can be obtained according to the short-term prediction of support vector machine and neural network method [12], the higher precision of three spline interpolation can avoid the instability of higher order polynomial, The $P_{PV}(t_i)$ analytical formula is obtained by fitting the three spline interpolation, and then the power value of the PV power is obtained at t_i time.

III. Fuzzy Model and Solution

C. Fuzzy Processing of the Model

The objective function to optimize the storage type (4) belong to multi-objective optimization problem, the optimal solution of multi-objective is related to the solution of each function, At the same time, there is a contradictory relationship between the operating cost and the variance of load change. This paper uses fuzzy mathematics [9] to solve this problem, the optimal solution for f_1 and f_2 first; Then according to the membership function of the optimal solution to write f_1 and f_2, which is the function of satisfaction; finally, the maximum value for satisfaction function, is the optimal solution to the model.

In this paper, the operating cost of the cold storage and the minimum load change as the goal, the smaller the target. So we need to choose the small size and lower Γ type distribution in all aspects of this paper.

$$\mu_k(t_i) = \begin{cases} 1 & f_k \le f_k^{\min} \\ \exp\left(\dfrac{f_k^{\min} - f_k}{f_k^{\min}}\right) & f_k > f_k^{\min} \end{cases} \tag{15}$$

where: the minimum value of $f_k^{\min}$ for f_k in the corresponding constraint condition, k=1, 2.

Based on the above analysis, the multi-objective model is transformed into a single objective function, then the optimization model can be written as

$$\max\ \mu(t_i) \quad s.t. \begin{cases} \mu(t_i) \le \mu_1(t_i) \\ \mu(t_i) \le \mu_2(t_i) \\ (4) \sim (14) \end{cases} \tag{16}$$

D. Particle Swarm Optimization

Because of the dimensions, variables and constraints of the function, the particle swarm optimization algorithm can solve the nonlinear optimization problem. Through the PSO to solve the optimization model of the cold storage [10], the optimal operation strategy of the cold storage is obtained, and the load power, large power purchase power, the storage battery power and the grid connected power are taken as the dimension of the particle. The position of the particle in the search space corresponds to the control variables of each type of power in the cold storage.

C. 0-1 Knapsack Algorithm

For compressor, cold storage of ammonia pump and pump specific load start and stop solution, into the 0-1 knapsack problem, the independent variables in the model are all integers, and the values were 0 and 1, said that the state of each load switch, the constraint conditions are the operating characteristics and operating conditions of each load in the cold storage, and the objective function is the minimum of the ideal power difference between the total load and the operating cost at the moment, expressed as

$$\min \quad \varepsilon = \sum_{j=1}^{n} P_j(t_i)x_j - P(t_i) \tag{17}$$

The constraint condition is formula (12) ~ (14). The use of LINGO software to calculate the start and stop of each load, through the PLC control the start and stop of each switch.

Optimal operation control specific implementation process of cold storage as shown in Fig. 2.

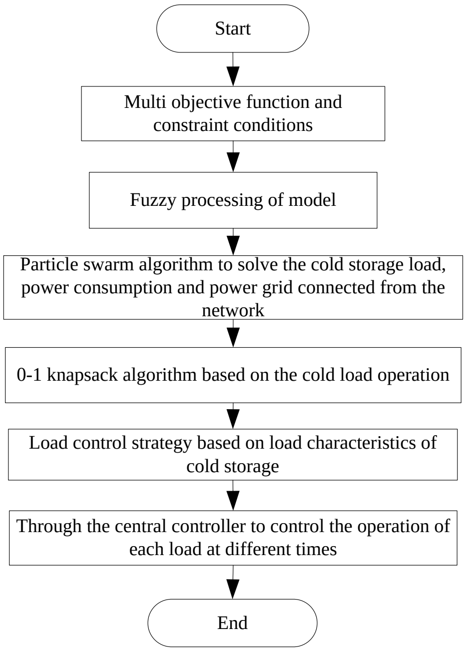

Figure 2. Optimal operation control specific implementation process of cold storage

II. EXAMPLE ANALYSIS

In this paper, a garlic trading market in Henan Province as an example, through the PSO algorithm to optimize the operation of the cold storage.

A. TOU Price

The peak and valley electricity price in Henan area mainly includes four periods of peak period, rush period, peace period and trough period, which is divided into 5 periods according to the price policy, as shown in Table I.

TABLE I. PEAK PERIOD DIVIDED FLAT VALLEY IN HENAN PROVINCE

Electricity consumption period	***Time slot***	***Electricity price (yuan /kWh)***
Peak period	18:00-22:00	1.3657
Rush period	8:00-12:00	1.2165
Peace period	12:00-18:00、22:00-24:00	0.7912
Trough period	0:00-8:00	0.4182

B. Parameter Setting and Calculation Analysis

Through the PSO algorithm to solve the model in this paper, the use of MATLAB7.10 programming, prediction of PV power value at different time in cold storage. According to the interval of 1 hours to give the day from 0:00 to 24:00 a total of 24 hours of operation plan. In this paper, the one day of off-season and peak season in cold storage as an example, cold storage of garlic, the storage temperature range of -3℃~1℃.

The data involved in the model calculation are obtained through the investigation of Henan electricity price and subsidy price, it's as follows: $\lambda_{PV} = \eta_{Bt} = \lambda_{Bt} = 0.9$; $P_{net}^{\max}(t_i) = 561.6kW$; $P^{\max}(t_i) = 761kW$; $J_{Bt} = 0.02 yuan/kWh$; $J_{PV} = 0.08 yuan/kWh$; $J_{an} = 0.39 yuan/kWh$; $J_{sub} = 0.42 yuan/kWh$; The maximum number of iterations in the particle swarm is 1000; the speed range is [0.4, 0.4]; P_c=0.7.

By solving the model, we can get the change curve of power consumption, load power and grid connected power with time in the off-season, which is shown in Fig. 3.

When the photovoltaic power generation is not added to the load control strategy, the cold storage market off-season purchase cost of 1560.6 yuan every day, use the PSO algorithm to obtain the load power, large power purchase power, Grid connected power and battery power optimization value, cold storage market in the off-season every purchase cost is -1551.6 yuan every day, saving the cost of 3112.2 yuan, the cost saving rate of 199.4%.

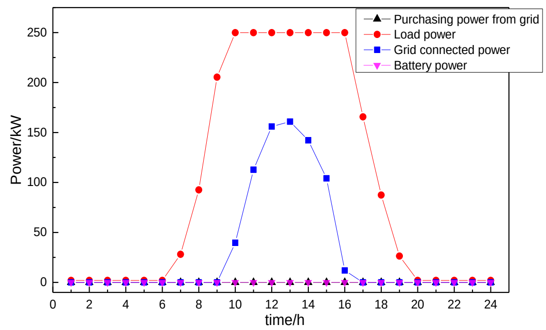

Figure 3. Off season operation optimization results of cold storage

By solving the model, we can get the curve of the large power purchase power, the load power and the grid connected power with the time in the peak season, as shown in Fig. 4.

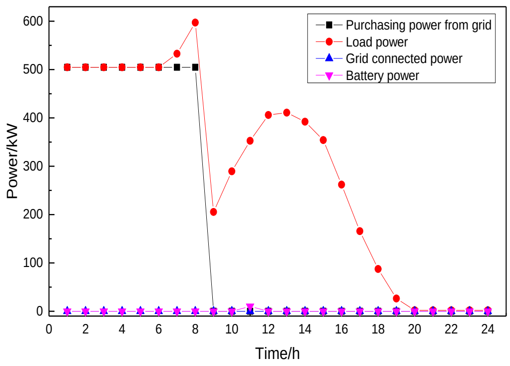

Figure 4. Busy season operation optimization results of cold storage

When the photovoltaic power generation is not added to the load control strategy, the market price of cold storage is 5352.8 yuan every day in the peak season, use the PSO algorithm to obtain the load power, large power purchase power, Grid connected power and battery power optimization value, cold storage market in the peak season every purchase cost is 393.8 yuan every day, saving the cost of 4959 yuan, the cost saving rate of 92.6%.

The standard deviation of the load before and after the optimal operation strategy is shown in Table II. The results show that the mean square error is small under the control strategy, can effectively achieve peak clipping and valley filling.

TABLE II. BUSY SEASON AND OFF SEASON OF COLD STORAGE CONTROL STRATEGY UNDER THE POWER PURCHASE POWER STANDARD DEVIATION

Electric power standard deviation	***No control strategy***	***Usage control strategy***
Off-season	60.3	53.6
Busy season	188.7	150.8

The 0-1 knapsack algorithm to calculate the load on the open cold storage, cold storage refrigeration capacity of different load with different proportion of open, are expressed as step 1~5 process.

C. The Influence of Different TOU Price on Cold Storage Operation Strategy

Taking into account the price of electricity and electricity purchase price in different regions, which leads to different control strategies of cold storage, there are 5 main modes of operation, namely I~V. Through the calculation found that when the battery does not consider the situation, the large electricity price is greater than the purchase price of photovoltaic electricity, photovoltaic power generation at the moment of control strategy for spontaneous use, the rest of the electricity is used to access the internet; If the PV power is not enough to buy electricity from the power grid. When the purchase price of large power grid is less than the price of photovoltaic electricity, at the moment the PV control strategy for all grid.

IV. CONCLUSION

This paper through analyzes the optimal control strategy of the cold storage system with photovoltaic power generation system, established multi objective optimal operation strategy for power grid load fluctuation and operation cost minimization, the membership function and particle swarm optimization are used to provide the basis for the operation strategy of cold storage. Finally, according to the 0-1 knapsack algorithm, the load control strategy is obtained. Taking a garlic trading market in Henan as an example, the results of the cold storage whether to adopt the optimal control strategy are analyzed and compared. The results show that the control strategy can reduce the operation cost, and effectively reduce the peak valley difference. Finally, the corresponding control strategies are obtained by comparing the electricity price and the user purchase price.

REFERENCES

[1] J. Y. Li, "Cold chain," *China Logistics*, vol. 2016, no. 2, 2015.

[2] J. S. Lee, S. Jeong, Y. H. Han, and B. J. Park, "Concept of cold energy storage for superconducting flywheel energy storage system," *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, pp. 2221–2224, 2010.

[3] P. Zhang, H. Jia, J. Li, A. B. Wu, and M. F. Xu, "Cold storage and release characteristics of a thermal battery unit using solid nitrogen and solid nitrogen impregnated in metal foam," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 4, 2016.

[4] Z. H. Deng and Y. Q. Zhang, "Research on the cold-storage door control based on frequency conversion technology," in *Proc. International Conference on Electronic and Mechanical Engineering and Information Technology*, Harbin, Heilongjiang, 2011, pp. 4512-4515.

[5] H. R. Dong, S. Qi, J. Ma, and S. Liu, "Study on energy saving in residential buildings in the cold district," in *Proc. International Conference on Advances in Energy Engineering*, Beijing, 2010, pp. 351-354.

[6] J. Xie, C. Miao, Z. Du, and J. Zhu, "Numerical simulation and parameter optimization on performance of air curtain in cold stores," *Journal of Agricultural Machinery*, vol. 45, no. 7, pp. 189-195, 2014.

[7] S. H. Duan, *et al.*, "research on optimal scheduling of combined cooling heating and power with photovoltaic power generation," *Proceedings of the CSU-EPSA*, vol. 25, no. 4, pp. 150-155, 2013.

[8] J. Lee, G. L. Park, S. W. Kim, H. J. Kim, and O. S. Chang, "Power consumption scheduling for peak load reduction in smart grid homes," in *Proc. 26th Annual ACM Symposium on Applied Computing*, TaiChung, 2011, pp. 584-588.

[9] S. Vluymans, *et al.*, "Fuzzy multi-instance classifiers," *IEEE Transactions on Fuzzy Systems*, vol. 24, no. 6, 2016.

[10] Y. N. Wang, Y. J. Chen, and Z. Q. Miao, "Obstacle avoidance planning for de-icing robot based on pso-fuzzy," *Control Engineering of China*, vol. 21, no. 2, pp. 298-302, 2014.

Bo Hu, Doctorate, he mainly studies load control and optimization. He works in State Grid Huludao Electric Power Supply Company, Huludao, China.

Liang Kong, Postgraduate education, he mainly studies load control and optimization. He is now studying at Northeastern University, He studied in Shenyang, China.