

Coordinated control method of low voltage distributed photovoltaic participating in market-oriented transaction

Zhifa Lin¹, Ping Chen¹, Hanqiu Wang¹, Mingyu Pan¹, Zhichao Chai¹, Xianglong Li¹ and Zhiming Zhao^{2,*}

¹State Grid Beijing Electric Power Research Institute, Beijing, China

²College of Information and Electrical Engineering, China Agricultural University, Beijing, China

Abstract. In the promotion of photovoltaic in the whole county, it is more and more important for distributed photovoltaic to participate in market-oriented transactions. Market based trading can realize the return on investment of users, promote the proportion of renewable energy, strengthen the willingness of time-shifting load to participate in source load interaction, and finally help to achieve the goal of carbon neutralization. In order to improve the local consumption capacity at the end of the power grid through market-oriented trading, this paper proposes a coordinated control method of local consumption based on multi-party cooperative game trading. The price is determined through the Stackelberg game between distributed photovoltaic investors, power grid and users, which is optimized by the improved particle swarm optimization method. The user value-added services are considered, the method of determining the revenue of value-added services by introducing load transfer coefficient, output increase proportion and power saving benefit coefficient is realized. Finally, an example is given to verify the effectiveness of the method.

Keywords: Coordinated control, Market transactions, Low-voltage power grids, Distributed photovoltaic.

1 Introduction

The access of many PV power sources makes the carrying capacity of the originally relatively weak low-voltage grid face a more serious challenge, and the intermittent nature of PV power generation further deteriorates the voltage quality of the low-voltage grid [1-2]. In addition, the access of local high percentage of distributed PV leads to lighter currents under the grid, with the possibility of backfeeding and even some changes in the load characteristics of the grid in some areas in severe cases, leading to further difficulties in balancing the supply and demand of the grid [3].

Based on the general background of PV consumption, this paper constructs the electricity trading strategy model and value-added service benefit model of market

* Corresponding author: SY20213081726@cau.edu.cn

participants based on the theory of Stackelberg game method, and solves the model by using tools such as particle swarm algorithm. Finally, we get the business model to realize PV consumption with win-win situation for both service providers and users.

2 A model of tariff trading strategy based on Stackelberg game method

On the price-driven side, the Stackelberg game method is used to find the optimal solution, in which a demand response price-driven model is needed to measure the demand-side electricity price response elasticity and determine the change in electricity caused by fluctuations in electricity prices.

2.1 Demand response price driven model

It is necessary to examine the extent to which local load is affected by fluctuations in electricity prices, and introduce a demand response price-driven model, i.e., to measure the extent to which users are driven by electricity prices by constructing a demand-side electricity price elasticity matrix.

The actual electricity consumption in each period after the implementation of time-sharing tariff can be obtained by equation (1).

$$\begin{bmatrix} Q_1' \\ Q_2' \\ \vdots \\ Q_n' \end{bmatrix} = \begin{bmatrix} Q_1 & & & \\ & Q_2 & & \\ & & \dots & \\ & & & Q_n \end{bmatrix} E \begin{bmatrix} \Delta p_1 / p_1 \\ \Delta p_2 / p_2 \\ \vdots \\ \Delta p_n / p_n \end{bmatrix} + \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_n \end{bmatrix} \quad (1)$$

In the formula, Q_i is the electricity consumption at the time point i , p_i is the price change at the time point i , Δp_i is the change of electricity price at the time point i . E is the electricity tariff elasticity matrix, n is the number of tariff division periods.

2.2 Determination of participants ' income function

2.2.1 Service provider income function.

For service providers, the revenue includes electricity sales revenue from users, electricity sales revenue from grid enterprises, and electricity purchase costs. Its income function formula is:

$$R_f = \sum_{i=fi} \sum_{j=pj} \sum_{k=gk} (p_f * q_i + p_p * q_j + p_g * q_k) + P_0 - c * \sum_{i=fi} \sum_{j=pj} \sum_{k=gk} (q_i + q_j + q_k) \quad (2)$$

In the formula, p_f , p_p , p_g are the unit electricity price sold by the service provider to the user (represents electricity purchase price of users) during the peak-valley period, P_0 are the electricity price income sold by the service provider to the grid enterprise, and c are the unit purchase cost of the service provider. Among them, the actual q_i , q_j , q_k is constrained by photovoltaic output.

2.2.2 User income function

In the electricity purchase transaction, the user 's income function is the negative value of electricity purchase cost, and the increase of this value means that the user 's electricity purchase cost is less. Its income function formula is:

$$R_c = -\sum_{i=f_i} \sum_{j=p_j} \sum_{k=g_k} (p_f * q_i + p_p * q_j + p_g * q_k) \quad (3)$$

2.3 Trading strategy based on Stackelberg game

The Stackelberg duopoly model requires the participating manufacturers to know each other's cost and market demand. In this model, two participants are mainly involved: leaders and followers. Stackelberg game method can be used to analyze the dynamic game of objects with different action orders, which is in line with the behavior in the power industry chain.

When the service provider knows the historical load demand of the user and can calculate its electricity price elasticity, the transaction strategy with the goal of maximizing the interests of the integrated energy service provider and the constraint condition of reducing the user 's power purchase cost is used to obtain the optimal solution of the market power transaction under this mode by Stackelberg game method.

2.4 Iterative solution based on improved particle swarm optimization algorithm

In this paper, the existing particle swarm optimization algorithm is partially improved, which improves the efficiency of the algorithm and has better performance for the optimal solution. The main improvements are as follows:

$$\omega = \omega_{mi} + (\omega_{max} - \omega_{min}) \cdot (gen - t) / gen \quad (4)$$

$$c_1 = c_{1max} - (c_{1max} - c_{1min}) \cdot (t / gen)^2 \quad (5)$$

$$c_2 = c_{1min} + (c_{1max} - c_{1min}) \cdot (t / gen)^2 \quad (6)$$

In the formula, *gen* is the number of iterations, *t* is the current iteration algebra.

The improved particle swarm optimization algorithm is used to simulate the game process between users and service providers. Through iterative optimization and continuously update the optimal selection of the two sides in the game process, and finally the optimal strategy of the two sides under the current constraint conditions is obtained in the solution space.

3 Value added service price

In terms of service driving, determine the pricing of value-added services by introducing load transfer coefficient, output increase proportion and power saving benefit coefficient.

3.1 Pricing scheme based on user value-added service benefit model

We consider that users can enjoy the contracted service of power management. Among them, the income from technical services is mainly divided into two parts: the income from

load transfer and the increase in user production brought by the improvement of planting effect. In the load transfer part, the degree of user load transfer is characterized by introducing the load transfer coefficient $load_tran$, and the reduction of power purchase cost caused by load transfer can be expressed by equation (7). The user's yield increase benefit brought by the improvement of planting effect can be characterized by the proportion of yield increase $production_inc$, and the specific calculation formula is shown in formula (8).

$$\Delta c_1 = load_tran * (p'_{10} - p_{10}) \quad (7)$$

$$\Delta r = production_inc * q_0 \quad (8)$$

p_{10} is the power purchase price for this period before the transfer, p'_{10} is the power purchase price for the new period after the transfer, q_0 is the user output before technical transformation.

The benefits of information value-added services mainly consider the energy-saving effect achieved through reasonable control of power use. The revenue increasing part of the service is characterized by introducing the power saving benefit coefficient, and the specific calculation method is shown in equation (9).

$$\Delta c_2 = -pow_save * p_{20} \quad (9)$$

In the formula, p_{20} is the power purchase price corresponding to the power saving period.

In the pricing of value-added services provided by service providers to users, considering the comprehensive trade-off of opportunity cost, users will choose the scheme with the largest consumer residual value [4]. Therefore, the price ceiling of the value-added service benefit model needs to be lower than the increase in production and income brought by the service to users and the reduction in power purchase cost, which can be expressed by equation (10).

$$P_H = \Delta r - \Delta c_1 - \Delta c_2 \quad (10)$$

The lower limit of the value-added service pricing is the lowest cost for the service provider to provide the service. Here, the corresponding man hour cost is mainly considered.

$$P_L = \sum salary \cdot man_hour \quad (11)$$

The service is mainly priced through profit redistribution, and the service profit division percentage is introduced to drive the win-win cooperation between users and service providers.

$$P_{ser} = per \cdot P_H (P_{ser} > P_L) \quad (12)$$

4 Model results analysis

4.1 The solution of the electricity price model between users and service providers

The daily income of the service provider in the best case is finally 108.60 RMB, the

corresponding peak-to-valley electricity prices are 0.7877 RMB/kWh, 0.4170 RMB/kWh and 0.2215 RMB/kWh.

The optimized peak-to-valley electricity price is finally obtained as shown in the table below.

Table 1. Comparison of electricity price in peak and valley period before and after game.

	Before the game (RMB/kWh)	After the game (RMB/kWh)
Peak	0.6564	0.7877
Flat	0.4389	0.4170
Valley	0.2215	0.2215

Under this model, the profit of the service provider is $R=108.60$ RMB/day; the average electricity price of electricity purchased by users is $C=0.3133$ RMB/kWh (the original average unit electricity purchase price was 0.4071 RMB/kWh)

The optimized peak-to-valley load distribution of users is as follows:

Table 2. Comparison of daily electricity consumption in peak and valley period before and after the game.

	Before the game(KW)	After the game(KW)
Peak	881.5250	852.5520
Flat	477.4750	504.5699
Valley	1073.3000	1147.1037

It can be seen from the results that the peak-to-valley pull-off ratio has changed from the original 0.8213 to 0.7432, a decrease of 9.51%. The daily load during peak hours has also changed from the original 881.5250kW to 852.5520kW, which has the effect of shaving peaks and filling valleys to a certain extent.

4.2 The solution of the pricing model of value-added services for users and service providers

The pricing of value-added services is determined mainly by redistributing the profits brought by the provided information and technical support services.

4.2.1 Earnings calculation

(1) Technical value-added services--benefits from load transfer

It can be found that for users, the monthly cost and benefit brought by value-added services is 948.12 RMB.

(2) Technical value-added services--the increase in user yield brought by the improvement of planting effect.

The yield increase ratio is taken as 5%, using formula (8), it can be obtained that the monthly equivalent income brought by the effect of increasing production is 1704.07 RMB.

(3) Revenue from information value-added services

Considering that the user's electricity saving is roughly 2% of the current user's electricity consumption, the monthly electricity purchase cost that can be saved by formula (9) is about 470.74 RMB. Substituting the above calculation into formula (10) shows that the comprehensive income of this service is 3122.93 RMB/month.

4.2.2 Cost calculation

(1) Information value-added services

Considering the labor cost of this value-added service, the main cost of information value-added service comes from the fixed cost of automation equipment input, and the benefits of long-term services are slowly recovered by equipment depreciation. In addition, the cost of providing power quality analysis services is equivalent to 4 man-hours.

(2) Technical value-added services

The technical support service is equivalent to about 22 man-hours. Calculated according to the average labor cost of 80 RMB/day in Gansu Province, the service cost that can be obtained by using formula (11) is 2080 RMB/month. From this, the monthly net income of the service can be obtained about 1042.93 RMB.

5 Conclusion

The main conclusions of this paper are as follows:

(1) Drive users to purchase electricity from service providers by formulating appropriate electricity prices, and at the same time change their electricity consumption habits by providing relevant value-added services, and realize the effect of maximizing the income of service providers through this model;

(2) Build a value-added service pricing model for users and service providers to increase the stickiness of cooperation between users and service providers, and price the value-added services provided by service providers in the form of redistribution of profits from services;

(3) This paper proposes to use the Stackelberg game method to establish a game model for power transactions between service providers and users. In the later stage, the introduction of blockchain technology can be considered for intelligent power transactions, so that power transactions at various points in time are more targeted and efficient.

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