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RESEARCH ON OPTIMIZATION MODEL OF THE LINKAGE TOU TARIFF UNDER THE MODE OF CHINA ELECTRIC POWER SYSTEM

Zhao Yang[1],Li Shushui [1], Hu Po[1],Zhang Xinyue[1],Zhao Haoran[2],Han Xiaoyu[2]
([1], State Grid Hubei Economic Research Institute, Shijiazhuang 050021, China;[2], North China Electric Power University,Beijing,102206,China)

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ABSTRACT
Under China's current power system mode, the current TOU tariff is mostly considered and formulated from the sale side or the generation side, TOU tariff of the linkage in generation side and the sale side has not yet occurred. In order to ensure that the implementation of TOU tariff can get the greatest social and economic benefits, and to ensure that the power generations and power grid and the user's interests are not impaired, we design a generation side linkage TOU tariff optimization model with Long-term social cost minimization as optimization objective, Short-term social cost minimization as constraints conditions. Based on the historical data in a certain area, the feasibility and rationality of the model are verified by a numerical example.

KEYWORDS: linkage TOU tariff; Short-term social cost ;Long-term social cost; peak valley tariff optimazation model

INTRODUCTION
With the continuous improvement of the electricity consumption proportion of the third industry and residents, the load curve of the power network presents a new change. At the aim of improving the power supply reliability, power quality and the load rate of power grid, various kinds of policy and regulations on demand side management have been carried out to guide consumers to use electricity appropriately. Time-of-use (TOU) tariff is an effective means of demand side management which formulates different price in different periods according to the demand difference of consumers in peak and valley period. The policy of TOU tariff plays a key role in peak clipping and valley filling, relieving the tight situation of electricity supply, increasing the load rate, improving the security and economy of power grid and enhancing the operation efficiency and stability of power system, thus achieving remarkable economic and social benefits.

However, most of China’s current TOU tariff policy were laid down from the perspective of the generation side and demand side unilaterally, therefore, the peak and valley electricity price of generation side were not linked with that of sale side which means that it is difficult for electricity price to reflect the production and transmission cost of electricity. Therefore, on the purpose of further promoting the implementation of TOU price policy and playing a part in peak shaving and valley filling, guiding the consumption of users and improving production efficiency, it is necessary to establish an optimization model of the linkage TOU tariff for generation side and demand side, solving the limitation problem of implementing peak and valley time price only from one aspect, balancing the benefit distribution between power generation enterprises and power grid corporations and further developing the superiority of TOU tariff.

In order to deal with the problems arising from the introduction of TOU tariff only from the sale side, the basic idea is to make an attempt to link the electricity price of generation side with that of sale side and balance the interests of power generation, power grid and consumers. Contemporarily, the research on this field can be divided as follows:

(1)Research on the cost and benefit of TOU tariff

The adjustment of TOU tariff is related to the interests of consumers, power grid corporations and power generation enterprises, therefore, the analysis of the influence of TOU tariff formulation on cost and benefit of related stakeholders is the premise to design TOU tariff for sale side and generation side. Tang etc. [14] established cost benefit analysis models for power grid corporations, power consumers, power generation enterprises and the whole society respectively and made a detailed introduction on the calculation process of cost benefit analysis. The cost of the implementation of the TOU tariff in the power grid corporations contains the investment cost of the related equipment, the expense of project management and the loss of sales revenue. Additionally, the benefit of power grid corporations include free volume cost and free electricity cost. The interests of electricity consumers and related benefits of the implementation of TOU tariff embrace the reduction of electricity expenditure, and the cost consists of cost of equipment investment assumed by users and the expenditure of project management which include the operation and maintenance cost increased by users and the overtime allowance paid to the workers due to the adjustment of electricity consumption mode. Steven D. Braithwaite [15] summarized the research methods of the benefit of residential consumers in time of use electricity consumption from the perspective of electricity price design and user response. For industrial consumers, Song [16] analyzed the purchase cost and the sale revenue of electricity reduced by TOU tariff and established analysis model about the influence of TOU tariff in demand side on the risk of purchasing and selling electricity in power supply corporations, the analysis results of which indicated that the reasonable determination of price gap rate and power purchase proportion in contract market can make power supply enterprises avoid risk effectively and improve operating efficiency.

(2)Research on the linkage optimization model of TOU tariff.

Wang etc. [17] established electricity distribution optimization model of power generation plant on the basis of accounting cost method and two-part electricity price, then put forward the design mechanism of TOU tariff and principles of electricity allocation in electricity generation side. Zeng etc. [18] established a peak and valley TOU tariff economic optimization model of the linkage between feed-in tariff and sale electricity price and presented linkage proposal based on the analysis of the influence of peak and valley time of use electricity price policy on the economic interests of sale side and generation side. Taking the economic losses caused by pollutants emitted by various kinds of units during the generation process into account and taking the minimum average cost of power generation after the implementation of peak and valley TOU tariff as the objective function, Tan [19] constructed an optimization model for designing peak and valley TOU tariff of generation side and sale side at the direction of energy conservation dispatch which was solved through employing genetic algorithm. In order to achieve the optimal load curve and balance the cost effectiveness between power generation companies and power supply corporations, Tan etc. [20] built a two level optimization model of power generation side and power supply side TOU tariff linkage and proved that this model can reasonably distribute the interests and risk of power generation side and power supply side. Liu etc. [21] proposed time of use pricing model of demand side and generation side electricity price linkage based on market clearing price, however, the essence of this model was based on cost method to account feed-in time of use price, which was taken as the reference of clearing and linkage. Chen etc. [22] and Chen etc. [23] presented the linkage model of bilateral TOU tariff from the perspective of the equilibrium distribution benefits between power generation companies and power grid corporations brought by the implementation of TOU tariff in electricity supply side. This is a kind of linkage method based on the cooperative game which requires the rational distribution of the interests between both sides of cooperation, therefore, this linkage will be able to continue. The analysis results demonstrated that power generation enterprises and power grid companies have obtained larger interests after linkage which was very conducive to encourage power plants and power grid to participate into time of use pricing system. Yang etc. [24] designed peak and valley TOU tariff in sale side based on the consideration of consumers behavior which would cause loss of grid, and gave some suggestions of designing peak and valley TOU tariff in sale side on the basis of cost allocation differences in power generation side at different time periods, however, the model of bilateral electricity price linkage has not been provided. Ehlen etc. [25] designed peak and valley TOU tariff beginning from generation side and deduced peak and valley TOU tariff of sale side linked with the generation side, however, the bilateral linkage price system obtained by this method weakened the effect of peak shaving and valley filling of TOU tariff in sale side, therefore, the social benefit increment would be sacrificed which ought to be achieved.

Considering the optimization design of the generation side and retail side peak and valley TOU tariff linkage system, this paper will account the social short term cost brought by TOU tariff, from the perspective of changes in the cost and benefit of power generation, power grid and consumers in producing, purchasing, and selling electricity before and after the adjustment of time of use price. Social long term cost caused by TOU tariff will be accounted from the perspective of the changes of environmental benefit, investment saving efficiency and system security benefit result from the adjustment of TOU tariff. Taking the minimum of the short-run social cost as the constraint conditions and the minimum of the long-run social cost as the objective function, dynamic optimization model of electricity price linkage with sale side and generation side will be established, then policy recommendations and implementation schemes of the residential peak and valley TOU tariff in somewhere will be presented in accordance with the output results of the model.

2 Model building

2.1 The demand response function of TOU tariff

Now, assuming that the daily peak, flat, valley period of the study area has been divided. Before the definition and calculation of the social costs associated with TOU tariff, the demand response function of the social peak and valley time is first introduced.

$$\begin{aligned} L_p &= F_p(\mathbf{P}) \\ L_f &= F_f(\mathbf{P}) \\ L_v &= F_v(\mathbf{P}) \\ \mathbf{P} &= (P_p, P_f, P_v) \end{aligned} \tag{1}$$

P_p, P_f, P_v,respectively, indicates that the average sales price(kWh/yuan) of the peak, flat, valley period of the area, the average sales price is the average value of the price of all kinds of users in the same period. L_p, L_f, L_v in accordance with the needs of the model complexity can be expressed as the average load of peak, flat, valley period of the study period(load unit is kW, low complexity model):

$$\mathbf{L}_p = (L_{p1}, L_{p2}, ..., L_{pi}, ..., L_{pn_p}) \tag{2}$$

$$\mathbf{L}_f = (L_{p1}, L_{p2}, ..., L_{pi}, ..., L_{pn_f}) \tag{3}$$

$$\mathbf{L}_v = (L_{p1}, L_{p2}, ..., L_{pi}, ..., L_{pn_v}) \tag{4}$$

n_p, n_f, n_v indicates the representative point collected in the peak, flat, valley period respectively.

Normally, the average load in a certain period is the monotonic non-increasing function of the price of the period, and it is a monotonic non-decreasing function of other period. Only when whole society electrical behavior with these two features, can a reasonable method of demand side TOU tariff be designed to guide all types of users to change the original power consumption way, and to get the aim of peak shaving and valley filling of social load curve in a certain extent.

2.2 Effect of TOU tariff to the costs and benefits of participating parties

At present, China's electricity trading mode is still hold by transmission and distribution integration, in this model, power grid plays an important role in electric power transaction and therefore when the demand side implements or adjusts TOU tariff policy, the cost and benefit of participating parties will be influenced.

(1)The effect of TOU tariff for demand side to the cost and benefit of the users and power grid.

The impact of the effect of TOU tariff for demand side to the users is mainly on the change of electricity expenditure. The main purpose of the implementation of TOU tariff is to shave the peak and to fill the valley, different periods with different electricity prices, users will tend to save electricity costs, therefore the power demand structure will be changed. Correspondingly, effect of TOU tariff for demand side is opposite to that of the electricity sales revenue of the power grid enterprises.

(2) The effect of TOU tariff for demand side to the costs and benefits of the generation enterprises and power grid.

Under the current power system transaction mode in our country, on-grid and electricity sale price still follow the basic principles of government pricing, electricity prices do not fluctuate with market supply and demand, therefore, TOU tariff for demand side mainly influences enterprises' purchase costs from the power grid line loss rate of power grid. Due to the implementation of the TOU tariff for demand side, the effect of peak shaving and valley filling is produced, and the rate of line loss decreased, when the on-grid electricity keep unchanged, purchase costs of the power grid enterprises will decrease with the loss rate of the electric decreases. Accordingly, the increment of sales revenue of generating units is the same as that of power grid enterprises in the opposite direction. Because the costs of power generation unit is also affected by the loss rate, in the process of load curve fluctuations gradually reduced, the loss of power units also decreased, thus, the cost of generating units may also decreased.

From the comprehensive analysis of the foregoing, we know that, under the integration of electricity power trade, the implementation of TOU tariff for demand side balanced the costs and benefits between users and the power grid enterprises, the costs and benefits between the power grid enterprises and the power generation enterprises, in the end, the overall benefits increment of the three are the increment of the negative one of power generation units' electricity generating costs, which means the three will get positive economic benefit. After analyzing the net income of users, power grid enterprises and power generation units, we can know that the user's electricity expenditure decline is a certainty, but how will the net income of the power grid enterprise and the power generation unit change is not sure, which needs further analysis.

2.3 The meaning and measurement of Short-term social cost

After the introduction of the social peak valley electricity price demand response function, then it can be defined and measured that the change of the cost benefit of users, power grid, power generations and other social benefits related to the implementation of peak and valley TOU tariff. To the need of the construction of the linkage optimization model for peak and valley TOU tariff, the Short-term social costs and the Long-term social costs should be defined and measured individually.

Short-term social cost can be defined as: Short term social cost increments due to the implementation of peak valley TOU tariff is the sum of changes in cost and benefit of power generation, purchase and sale of electricity of users, power grid, power generations and other social stakeholders.

From the above definition, Short-term social cost increment due to the implementation of peak valley TOU tariff is essentially re-distribution of benefits among users, power grid and power generations in the purchase and sale of electricity caused by the peak-valley adjustment of Benchmark electricity price, sales price, which can change significantly during a short time. Here we think that the existing of the incremental benefit of electricity buying and selling between users, power grid and power generations will not bring the external effect.

When the interests of all parties were accounted separately, the incremental benefit of the response may be positive, or negative. For different stakeholders, the interests should be measured according to their specific circumstances:

(1) Incremental measurement of power consumption cost

The average selling price for each period of time before the electricity price is adjusted or implemented on the sales side of the electricity market is:

$$\mathbf{P}^0 = (P_p^0 \quad P_f^0 \quad P_v^0) \tag{5}$$

In this area, the total power consumption of peak, flat and valley periods is:

$$\mathbf{Q}^0 = (Q_p^0 \quad Q_f^0 \quad Q_v^0) \tag{6}$$

Among them, the price vector of the three components in accordance with the specific circumstances of the study area, may be equal, but also may vary. Sale price after the adjustment of the peak valley TOU tariff on the sale side is as formula (7).

The cost of purchase and sale of electricity (in the period of the study) caused by the implementation or adjustment of peak valley TOU tariff is:

$$\Delta CC = \mathbf{P} \cdot \boldsymbol{TF}(\mathbf{P}) - \mathbf{P}^0 \cdot (\mathbf{Q}^0)^T \qquad (7)$$

Where,

$$\boldsymbol{TF}(\mathbf{P}) = \begin{bmatrix} T_p \cdot F_p(\mathbf{P}) \\ T_f \cdot F_f(\mathbf{P}) \\ T_v \cdot F_v(\mathbf{P}) \end{bmatrix} \qquad (8)$$

T_p 、 T_f 、 T_v, respectively, indicates that the duration of each period of the study period, peak, flat, valley (unit: H). Because most of China's independent operating electricity selling companies have not yet appeared, therefore, for the sake of simplicity, and no loss of the meaning of analysis, here that all kinds of users of the community are the end consumers of electricity, there is no revenue of electricity selling, but the incremental revenue of selling the electricity generated due to the implementation or adjustment of peak valley TOU tariff:

$$\Delta CI = 0 \qquad (9)$$

As a result, the incremental benefits of the purchase and sale of electricity consumers due to the implementation or adjustment of peak and valley TOU tariff:

$$\begin{aligned} \Delta CR &= \Delta CI - \Delta CC \\ &= -[\mathbf{P} \cdot \boldsymbol{TF}(\mathbf{P}) - \mathbf{P}^0 \cdot (\mathbf{Q}^0)^T] \\ &= \mathbf{P}^0 \cdot (\mathbf{Q}^0)^T - \mathbf{P} \cdot \boldsymbol{TF}(\mathbf{P}) \end{aligned} \qquad (10)$$

(2) Measurement of the sales incremental revenue of the Power Grid

Before and after the implementation or adjustment of peak valley TOU tariff, the sales revenue of the power grid in the research period will be changed accordingly:

Power grid peak hour's sales revenue change:

$$\Delta GI_p = P_p T_p F_p(\mathbf{P}) - P_p^0 Q_p^0 \qquad (11)$$

Power grid flat hour's sales revenue change:

$$\Delta GI_f = P_f T_f F_f(\mathbf{P}) - P_f^0 Q_f^0 \qquad (12)$$

Power grid valley hour's sales revenue change:

$$\Delta GI_v = P_v T_v F_v(\mathbf{P}) - P_v^0 Q_v^0 \qquad (13)$$

(3) Measurement of the power grid incremental cost of purchase
Before accounting for this part of the incremental costs, it is necessary to carry out the following instructions:
First of all, use the difference of original benchmark price to classify each power plant (crew) in power grid

scheduling diameter, power plants who has a same original benchmark price are of a class, which ends up a classification of N groups, each of the groups are called a generating unit.

Second, we considered that power plants in the same group should have the same TOU tariff after the adjustment or implementation; 2) under the principal above, the resource allocation of the TOU tariff couldn't be applied to the unified power generation units within the power plant (crew); 3) When the demand response makes the period of the cycle of social electricity consumption change, the ideal principle of output distribution is each unit share the incremental quantity equally by proportion of annual plan (contract) power generation.

However, during the actual operation, the power network dispatching center will be subject to various objective random factors when making decisions, and thus it is difficult to guarantee the actual cycle scheduling to strictly implement the above principal 3). Therefore, in the process of actual measurement and modeling, the proportion of each generation unit in the increment of power consumption in each period of time should be related to a certain range of variables. In order to establish the foundation for the analysis of the uncertainty of the sensitivity analysis.

Set the tariff before and after the adjustment of peak and valley time period of the ith (i=1,2,…,N) generating unit are, p_i^0 , $\boldsymbol{p}_i$,Where vector is:

$$\boldsymbol{p_i} = (p_{pi}, p_{fi}, p_{vi}) \tag{14}$$

Where, p_{pi}, p_{fi}, p_{vi} respectively expressed the peak, flat, valley price of the ith (i=1,2,…,N) generating unit.

The average loss rate of peak, flat and valley periods are set as $\alpha_p, \alpha_f, \alpha_v$, then before and after the implementation or adjustment of peak valley electricity price, the purchase cost of the power grid will also change, the increment of each time period is like (15), (16), (17).

Peak period cost variation:

$$\Delta GC_p = \sum_{i=1}^{N} [p_{pi} T_p F_p(\mathbf{P})(1-\alpha_p)^{-1} \lambda_i - p_i^0 Q_p^0 (1-\alpha_p)^{-1} {\lambda^0}_i] \tag{15}$$

Flat period cost variation:

$$\Delta GC_f = \sum_{i=1}^{N} [p_{fi} T_f F_f(\mathbf{P})(1-\alpha_f)^{-1} \lambda_i - p_i^0 Q_f^0 (1-\alpha_f)^{-1} {\lambda^0}_i] \tag{16}$$

Valley period cost variation:

$$\Delta GC_v = \sum_{i=1}^{N} [p_{vi} T_v F_v(\mathbf{P})(1-\alpha_v)^{-1} \lambda_i - p_i^0 Q_v^0 (1-\alpha_v)^{-1} {\lambda^0}_i] \tag{17}$$

Where, ${\lambda^0}_i$ and λ_i (i=1,2,…,N) represent the proportions before and after the adjustment of peak valley time period that the sum of power generation at each time period for the ith (i=1,2,…,N) generating unit of the that of the total power generations. The value is randomly distributed in a certain range. Obviously:

$$\sum_{i=1}^{N} {\lambda^0}_i = 1 , \quad \sum_{i=1}^{N} \lambda_i = 1 \tag{18}$$

The profit increment of the power grid in the research period is:

$$\begin{aligned} \Delta GR &= \Delta GR_p + \Delta GR_f + \Delta GR_v \\ &= \sum_{t=p,f,v} (\Delta GI_t - (\Delta GC_t)) \end{aligned} \tag{19}$$

（4）Increment measurement of sales revenue in power generation unit

From the total amount of numerical value, electricity sales revenue of the power generation side is the purchase cost of electricity for the power grid corporations. However, in the case of specifically analyzing the situation of a single generation unit, because of the difference in the power generation and the electricity price of each unit, measuring the increment of the sales revenue of the unit is required.

Before and after the implementation and adjustment of the peak valley time of use electricity price in the power system, the sales revenue of generation unit i（i=1,2,⋯,N）will change, and the increment of each time period are as follows:

the income variation of peak period:

$$\Delta PI_p = p_{pi} T_p F_p(\mathbf{P})(1-\alpha_p)^{-1}\lambda_i - p_i^0 Q_p^0 (1-\alpha_p)^{-1}\lambda^0{}_i \qquad (20)$$

the income variation of flat period:

$$\Delta PI_f = p_{fi} T_f F_f(\mathbf{P})(1-\alpha_f)^{-1}\lambda_i - p_i^0 Q_f^0 (1-\alpha_f)^{-1}\lambda^0{}_i \qquad (21)$$

the income variation of valley period:

$$\Delta PI_v = p_{vi} T_v F_v(\mathbf{P})(1-\alpha_v)^{-1}\lambda_i - p_i^0 Q_v^0 (1-\alpha_v)^{-1}\lambda^0{}_i \qquad (22)$$

（5）Power generation cost increment measurement in power generation unit

Setting that there are n_i (n_i are positive integers) assembling units in the class of i（i=1,2,⋯,N）power generation unit and the average unit costs of power generation of assembling unit j(j=1,2,…,) during peak, flat and valley period are $c_{pi}^{(j)}$ 、 $c_{fi}^{(j)}$ 、 $c_{vi}^{(j)}$. The proportion of annual planned power generation in the power generation unit is $\lambda_i^{(j)}$, significantly,

$$\sum_{j=1}^{n_i} \lambda_i^{(j)} = 1 \qquad (23)$$

Therefore, the average unit costs of power generation of the class i（i=1,2,⋯,N）power generation unit during peak, flat and valley period can be approximately expressed as:

$$c_{pi} = \sum_{j=1}^{n_i} c_{pi}^{(j)} \lambda_i^{(j)} \qquad (24)$$

$$c_{fi} = \sum_{j=1}^{n_i} c_{fi}^{(j)} \lambda_i^{(j)} \qquad (25)$$

$$c_{fi} = \sum_{j=1}^{n_i} c_{fi}^{(j)} \lambda_i^{(j)} \qquad (26)$$

Then the increment of the cost of power generation before and after the implementation and adjustment of the peak valley time of use electricity price can be shown as follows

the cost variation of peak period

$$\Delta PC_{pi} = c_{pi} T_p F_p(\mathbf{P})(1-\alpha_p)^{-1}\lambda_i - c_{pi} Q_p^0 (1-\alpha_p)^{-1}\lambda^0{}_i \qquad (27)$$

the cost variation of flat period:

$$\Delta PC_{fi} = c_{fi} T_f F_f(\mathbf{P})(1-\alpha_f)^{-1} \lambda_i - c_{fi} Q_f^0 (1-\alpha_f)^{-1} \lambda^0{}_i \qquad (28)$$

the cost variation of valley period:

$$\Delta PC_{vi} = c_{vi} T_v F_v(\mathbf{P})(1-\alpha_v)^{-1} \lambda_i - c_{vi} Q_v^0 (1-\alpha_v)^{-1} \lambda^0{}_i \qquad (29)$$

The profit increment for the class i（i=1,2,⋯,N）generation unit in the study period is:

$$\begin{aligned}\Delta PR_i &= \Delta PR_{pi} + \Delta PR_{fi} + \Delta PR_{vi} \\ &= \sum_{t=p,f,v} (\Delta PI_{ti} - \Delta PC_{ti})\end{aligned} \qquad (30)$$

2.4 The definition and measurement of long term social costs

Implementation and adjustment of TOU tariff not only change the costs and benefits (Short-term social costs) of generating, purchasing and selling electricity of users, grid companies and power companies, but also cause changes in other social costs or benefits, namely Long-term social costs discussed in this section.

Long-term social costs can be defined as: Incremental Long-term social costs resulting from the implementation of TOU tariff refers to the sum of other interest increments of users, power grid, power generations and other related parties (external) besides the sum of costs and benefits of generating, purchasing and selling electricity.

From the foregoing analysis, If stakeholders of Short-term social costs are clear and time of Short-term social costs is clear (approximately can be considered to occur at the same time along with demand-side response), quantity calculation is more convenient and more easily understood. However, due to ambiguous stakeholders (Long-term cost contains a lot of external costs or benefits) and uncertain time (some Long-term costs may appear after a long period of time, such as environmental improvement) in Long-term costs calculation as well as many implicit and unable accurately evaluated cost factors (e.g. how much environment benefits $1m^3$ SO_2 gas emission reduction can bring) and so on, Long-term costs cannot be very precisely and comprehensively measured.

According to the definition of the Long-term social costs in this paper, and the research results on the real-time effect evaluation of TOU tariff from a large number of domestic and foreign studies, in the Long-term social cost savings, what account for a large proportion and easily measured are free capacity costs of power system and environmental benefits, which are separately accounted as follows:

(1)The free capacity costs of power system

The free capacity (fixed) costs of power system mainly include the free capacity (fixed) costs of power grid and the free capacity (fixed) costs of power generations.

The free capacity (fixed) costs of power grid companies refer to the reduced investment costs of power grid for users decrease peak load of the whole society and improve valley load in respond to the new TOU tariff. The free gird capacity costs can be determined by the free system power capacity (load) multiplied by unit capacity average cost of the reduced or postponed construction of substations, transformers, transmission lines and ancillary equipment. In addition, the free system power capacity is associated with the peak load, user simultaneous rates and system reserve capacity coefficient. The specific calculation formula can be expressed as:

$$\Delta L_G = \frac{(L_p^0 - F_p(\mathbf{P}))\sigma}{(1-\gamma)(1-\alpha_p)} \qquad (31)$$

$$L_p^0 = \frac{Q_p^0}{T_p} \qquad (32)$$

From equation (31), the free capacity costs of power grid companies are calculated as follows:

$$\Delta GI_C = \Delta L_G \times \beta = \frac{(L_p^0 - F_p(\mathbf{P}))\sigma\beta}{(1-\gamma)(1-\alpha_p)} \qquad (33)$$

Where, β is the discount factor of the free gird capacity costs, namely the unit capacity average cost of power gird constructing substations, transformers, transmission lines and ancillary equipment.

The free capacity (fixed) costs of power generation companies refer to the power investment costs of power generation companies, which can be determined by the free system power capacity multiplied by unit capacity average cost of the reduced or postponed construction of peaking units and its' ancillary equipment. The formula is as follows:

$$\Delta PI_C = \Delta L_G \times \beta' = \frac{(L_p^0 - F_p(\mathbf{P}))\sigma\beta'}{(1-\gamma)(1-\alpha_p)} \qquad (34)$$

Where β' is the discount factor of the free capacity costs of power generation companies, namely the unit capacity average cost of power generation companies constructing peaking units and its' ancillary equipment.

(1)The environmental benefits

The implementation of demand response measures based on TOU tariff can effectively reduce the energy consumption and greenhouse gases emissions, reduce the degree of pollution to the environment from large-scale use of fossil fuel, and promote energy conservation, emission reduction and environmental protection. The environmental benefits brought by the TOU tariff are mainly the reduction of harmful gases and waste emissions due to the reduction of the power generation amount from the fossil fuel after the implementation of TOU tariff. In practical calculation, the emission reductions generated by the implementation of TOU tariff is mainly calculated through the emission reductions of CO_2, SO_2, NOx and other pollutant gases. According to the available energy savings based on demand response implementation of TOU tariff, and determine the corresponding pollutant emission factor or emission coefficient, then the actual emission reductions can be calculated. In this paper, the product of the emission reductions of CO_2, SO_2, NOx and other pollutant gases and the emission reduction value (can be understood as the unit pollution control cost of pollutant gases) is regard as the total emission reduction benefits brought by implementing demand response measures based on TOU tariff. Among them, the emission reductions of CO_2, SO_2, and NOx and other pollutant gases can be approximately calculated by the following formula (SO_2 emission reductions as an example):

Before and after the ith generating unit implement TOU tariff, the SO_2 emission variations in peak period are:

$$N^{(i)}{}_{p,SO_2} = \frac{\varphi_{SO_2}}{(1-\alpha_p)} T_p F_p(\mathbf{P})\mu_p\lambda_i - \frac{\varphi_{SO_2}}{(1-\alpha_p)} Q_p^0 \mu_p \lambda^0{}_i \qquad (35)$$

Before and after the ith generating unit implement TOU tariff, the SO_2 emission variations in flat period are:

$$N^{(i)}{}_{f,SO_2} = \frac{\varphi_{SO_2}}{(1-\alpha_f)} T_f F_f(\mathbf{P})\mu_f\lambda_i - \frac{\varphi_{SO_2}}{(1-\alpha_f)} Q_f^0 \mu_f \lambda^0{}_i \qquad (36)$$

Before and after the ith generating unit implement TOU tariff, the SO_2 emission variations in valley period are:

$$N^{(i)}{}_{v,SO_2} = \frac{\varphi_{SO_2}}{(1-\alpha_v)} T_v F_v(\mathbf{P}) \mu_v \lambda_i - \frac{\varphi_{SO_2}}{(1-\alpha_v)} Q_v^0 \mu_v \lambda^0{}_i \qquad (37)$$

Whereμ（t=p,f,v）are respectively the standard coal (T/kWh) of coal-fired units consumed by per unit of electricity in peak period, flat period and valley period; φ_{SO_2} is the SO_2 emissions from burning per unit of standard coal.

Before and after the ith generating unit implement TOU tariff, the SO_2 emission variations in whole period are:

$$N^{(i)}{}_{SO_2} = N^{(i)}{}_{p,SO_2} + N^{(i)}{}_{p,SO_2} + N^{(i)}{}_{p,SO_2} \qquad (38)$$

After calculated, $N^{(i)}{}_{SO_2}$ is usually negative, which indicates SO_2 emissions decline after reasonably implementation or adjustment of TOU tariff.

Therefore, before and after implementing TOU tariff, the environmental benefits generated by the ith generating unit are:

$$N^{(i)} = N_{CO_2} \times v_{CO_2} + N_{SO_2} \times v_{SO_2} + N_{NO_X} \times v_{NO_X} \qquad (39)$$

Where v_{CO_2} , v_{SO_2} , v_{NO_X} are respectively the emission reduction value (can be understood as the unit pollution control costs of pollutant gases) of CO_2, SO_2 and NOx. If $N^{(i)}$ is negative, it demonstrates that TOU tariff dose bring environmental benefits of reducing pollutant emissions (positive environmental benefits). In this case, the absolute value $|N^{(i)}{}_{SO_2}|$ represents positive environmental benefits, while $-|N^{(i)}{}_{SO_2}|$ represents negative environmental benefits.

2.5 The mathematical meaning of the minimum of Long-term social costs

The increment of Long-term social costs is mainly consists of power system capacity cost free and environmental benefit. Therefore, Long-term social costs can be in hole indicated as:

$$\begin{aligned}\Delta LC &= \frac{(L_p^0 - F_p(\mathbf{P}))\sigma\beta}{(1-\gamma)(1-\alpha_p)} + \frac{(L_p^0 - F_p(\mathbf{P}))\sigma\beta'}{(1-\gamma)(1-\alpha_p)} \\ &+ \sum_{t=p,f,v} \frac{\varphi_{SO_2}}{(1-\alpha_t)} Q_t^0 \mu_t \lambda^0{}_i - \sum_{t=p,f,v} \frac{\varphi_{SO_2}}{(1-\alpha_t)} T_t F_t(\mathbf{P}) \mu_t \lambda_i + \ldots\ldots\end{aligned} \qquad (40)$$

Note: Ellipses in the formula (40) indicated other environmental benefits whose accounting formulae are similar with SO2.

Similar as the Short-term costs, formula (40) can also be indicated as:

$$
\begin{aligned}
\Delta LC = & \frac{(L_p^0 - F_v(\mathbf{P}) - \Delta L_1)\sigma\beta}{(1-\gamma)(1-\alpha_p)} + \frac{(L_p^0 - F_v(\mathbf{P}) - \Delta L_1)\sigma\beta'}{(1-\gamma)(1-\alpha_p)} \\
& + \sum_{t=p,f,v} \frac{\varphi_{SO_2}}{(1-\alpha_t)} Q_t^0 \mu_t \lambda^0{}_i - \frac{\varphi_{SO_2}}{(1-\alpha_p)} T_p (F_v(\mathbf{P}) + \Delta L_1) \mu_p \lambda_i \\
& - \frac{\varphi_{SO_2}}{(1-\alpha_f)} T_f (F_v(\mathbf{P}) + \Delta L_1 - \Delta L_2) \mu_f \lambda_i - \frac{\varphi_{SO_2}}{(1-\alpha_v)} T_v F_v(\mathbf{P}) \mu_v \lambda_i \\
& + \ldots\ldots
\end{aligned} \tag{41}
$$

Partial derivate $F_p(\boldsymbol{P})$ and ΔL_1 of the formula (41), got:

$$
\frac{\partial \Delta LC}{\partial F_p(\mathbf{P})} = \frac{-\sigma\beta - \sigma\beta'}{(1-\gamma)(1-\alpha_p)} - \frac{\varphi_{SO_2}}{(1-\alpha_p)} T_p \mu_p \lambda_i - \ldots\ldots < 0 \tag{42}
$$

$$
\frac{\partial \Delta LC}{\partial \Delta L_1} = \frac{-\sigma\beta - \sigma\beta'}{(1-\gamma)(1-\alpha_p)} - \frac{\varphi_{SO_2}}{(1-\alpha_p)} T_p \mu_p \lambda_i - \frac{\varphi_{SO_2}}{(1-\alpha_f)} T_f \mu_f \lambda_i - \ldots < 0 \tag{43}
$$

From formulae (42) and (43) can we get that the increment of Long-term social costs will increase with the decline of the after-demand-response average social load, and increase with the decline of peak and valley load difference at the same time.

In general, the partial derivation of the total cost savings resulting from the implementation of peak valley electricity price to the after-demand-response social peak period average load is:

$$
\frac{\partial \Delta C}{\partial F_p(\mathbf{P})} = \frac{\partial \Delta SC}{\partial F_p(\mathbf{P})} + \frac{\partial \Delta LC}{\partial F_p(\mathbf{P})} < 0 \tag{44}
$$

The partial derivation of the total cost savings resulting from the implementation of peak valley electricity price to the after-demand-response difference between social peak period average load and social valley period average load is:

$$
\frac{\partial \Delta C}{\partial \Delta L_1} = \frac{\partial \Delta SC}{\partial \Delta L_1} + \frac{\partial \Delta LC}{\partial \Delta L_1} < 0 \tag{45}
$$

Therefore, considering from the angel of formulating the TOU tariff, the TOU tariff designed should meet the demand that: after demand response, the social load peak and valley difference will decrease, and the increment of Long-term social costs brought by it can be increasing, which is efficient for resource allocation.

However, an in-ignorable one is that even if the formulation of peak valley time price system can bring long-term cost savings, in the short term, there may be serious unfairness in distribution of incremental benefits in the development, purchase and sale of electricity between the users, power grid and power generations (The incremental benefit of one or some of the parties may be negative, resulting in a loss in a short period of time). Therefore, under the request of basic principles as "efficiency priority, taking into account fairness", the principle of minimum social cost for the formulation of peak valley electricity price system can be expressed as:

$$
\begin{aligned}
&\min \quad \Delta L_1 = F_p(\mathbf{P}) - F_v(\mathbf{P}) \\
&\min \quad F_p(\mathbf{P}) \\
&s.t. \quad \Delta GR = \sum_{t=p,f,v} \{P_t T_t F_t(\mathbf{P}) - P^0_t Q^0_t - \sum_{i=1}^{N} [p_{ti} T_t F_t(\mathbf{P})(1-\alpha_t)^{-1}\lambda_i - p_i^0 Q_t^0 (1-\alpha_t)^{-1} \lambda^0_i]\} \geq 0 \\
&\quad \Delta PR_i = \sum_{t=p,f,v} [p_{pi} T_p F_p(\mathbf{P})(1-\alpha_p)^{-1}\lambda_i - p_i^0 Q_p^0 (1-\alpha_p)^{-1} \lambda^0_i - c_{pi} T_p F_p(\mathbf{P})(1-\alpha_p)^{-1}\lambda_i + c_{pi} Q_p^0 (1-\alpha_p)^{-1} \lambda^0_i] \geq 0 \quad \forall i \quad (46) \\
&\quad \Delta CR = \Delta CI - \Delta CC \\
&\quad = -[\mathbf{P} \cdot \boldsymbol{TF}(\mathbf{P}) - \mathbf{P}^0 \cdot (\mathbf{Q}^0)^T] \\
&\quad = \mathbf{P}^0 \cdot (\mathbf{Q}^0)^T - \mathbf{P} \cdot \boldsymbol{TF}(\mathbf{P}) \geq 0 \\
&\quad F_p(\mathbf{P}) - F_v(\mathbf{P}) \geq 0
\end{aligned}
$$

It can be inferred from formula (46) that under the current vertical integration power system in china, the electricity price of generation side does not appear in the objective function of the model. Thus, the solution of the model can be divided into two steps: The first step is to solve the objective function and related to the user and the Power Grid Corp of the income distribution constraints, in order to get the best TOU price of the demand side; The second step is to solve the constraint conditions of the principle of fairness between the Power Grid Corp and the power generating units to meet the incremental income distribution, and get the feasible set of electricity price of each generation unit. In principle, any peak valley pricing scheme in the feasible concentration is an optimal linkage price which meets the “efficiency priority, taking into account fairness”. Such linkage price may exist infinitely many, we do not need to be able to enumerate them, only find a typical linkage price is feasible. Therefore, the calculation of this step does not need to solve the inequality equations directly, we only need to list some of the alternative price linkage program, and then, according to the principle of fairness among the interests of the Power Grid Corp and the power generating units, to screen out the pricing scheme to meet the corresponding constraint conditions.

3 example analysis

3.1 data base

In order to carry out the simulation calculation of the peak valley TOU price linkage optimization design model established in section2, and to get a regional peak valley electricity price linkage program system, the required basic data should be collected first. Based on peak valley time price linkage optimization model, the important data used in the calculation analysis are listed and briefly analyzed.

(1) Peak valley TOU tariff combination

The linkage design between the peak valley time price and the electricity generation side of the electricity generation unit is analyzed as an example. According to the calculation of formula (46), the peak valley TOU tariff under the three price ladder that is optimal peak-shaving, which also meets the users and the power grid incremental revenue distribution fairness principle, can be obtained first, as shown in table 1:

Table1 Optimal step peak valley pricing scheme for the demand side

Unit: yuan / kWh

grade	Price of peak	Price of flat	Price of valley

1	0.6125	0.49	0.3675
2	0.729	0.54	0.351
3	0.9875	0.79	0.5925

(2) The price of power generation enterprises and the classification of power generation units

In order to design the constraint conditions of the power generation unit in the peak valley TOU price linkage optimization model, and to lay the foundation for the calculation of Short-term and Long-term cost of generating units, the benchmark price of the power generation enterprises should be collected, and power companies should be classified in accordance with the benchmark price.

According to the catalogue distribution of coal and gas in the area in 2016, all power generation enterprises in the area are divided into 7 categories, each category is a generating unit, a generating unit contains the same set of electricity prices. Adjusted coal, gas electricity price as shown in table 2:

Table 2 Electricity price of coal and gas power generation and power generation unit classification

Classification number	Benchmark price (yuan/kWh)	Enterprise name	Installed capacity
1	0.3614	Company A	30.0
		Company B	70.0
		Company C	80.0
		Company D	70.0
		Company E	66.0
	0.3514	Company F	30.0
		Company G	3.0
2	0.4062	Company H	30.0
	0.4162		30.0
3	0.4252	Company I	50.0
	0.4152		50.0
4	0.3872	Company J	131.40
5	0.3394	Company K	10.0
		Company L	6.0
6	0.4424	Company M	6.5
7	0.7300	Company N	184.0
		Company O	5.6

(3) The proportion of annual generation of 7 types of generating units

The 7 types of generating units in the region accounted for the proportion of total cycle power generation as shown at table 3:

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Table 3 the proportion of total cycle power generation

i	Benchmark price (yuan/kWh)	λ_i (%)
1	0.3815	47.18
2	0.4363	9.72
3	0.3915	18.66
4	0.4073	21.97
5	0.3695	1.16
6	0.4673	0.50
7	0.7300	0.81

(4) The average unit power generation cost of 7 types of generating units at peak, flat and valley periods
The average unit power cost data of 7 types of generating units in the area of peak, flat and valley. As shown in table 4:

Table 4 the average unit power cost of peak, flat and valley

Unit：yuan/kWh

i	Power generation cost			Benchmark price (yuan/kWh)
	peak	flat	valley	
1	0.3719	0.3719	0.3719	0.3614
2	0.3407	0.3407	0.3407	0.4162
3	0.3285	0.3285	0.3285	0.4252
4	0.3355	0.3355	0.3355	0.3872
5	0.3967	0.3967	0.3967	0.3394
6	0.7189	0.7189	0.7189	0.4424
7	0.8659	0.8659	0.8659	0.7300

On the basis of the data required by the model calculation, using MATLAB programming, the results of the calculation of peak valley TOU price linkage optimization model were obtained.

3.2 Simulation calculation of peak valley TOU price linkage optimization model

(1) Feasible scheme and screening of the TOU tariff linkage considered the interests of all parties
As the region's current power generations in accordance with the current benchmark price is divided into 7 types of power generation unit, so the calculation of peak and valley time price linkage optimization system should also be carried out respectively on the 7 types of power generation unit.

First of all, on the basis of the existing benchmark price to define the floating ratio, define a β to represent the floating ratio of the price of the Internet, the existing benchmark price is used as the price of flat, price of peak floated (1+β) times on the basis of this and price of valley fell (1-β) times on the basis of this(5, 6, 7 generation unit due to its cost, the special price fall valley period (1-0.5β) times). If the 0.02 is set to the step size, the 0.5 is set to the upper limit, the number of alternative schemes for the 7 generation unit floating ratio value combination is 257. Table 5 lists some of the alternative price adjustment program:

Table 5 Part of the alternative price adjustment program expressed by β

Division	β						
β_1	0.02	0.04	0.06	0.08	…	…	0.50
β_2	0.02	0.04	0.06	0.08	…	…	0.50
β_3	0.02	0.04	0.06	0.08	…	…	0.50
β_4	0.02	0.04	0.06	0.08	…	…	0.50
β_5	0.02	0.04	0.06	0.08	…	…	0.50
β_6	0.02	0.04	0.06	0.08	…	…	0.50
β_7	0.02	0.04	0.06	0.08	…	…	0.50

On the basis of the constraint that the increments of interests of power grid and all power generation units should be no less than zero after the adjustment of TOU tariff, screen the possible value of β, the screened effective price floating ratio as shown in table 6, any situation in the table is corresponding to a comprehensive consideration of the interests of the power grid and all power generation units are not a loss of alternative price adjustment program:

Table 6 Float ratio β of Internet tariff

Divisions	Situations								
	1	2	3	4	5	6	7	8	9
β_1	0.02	0.04	0.04	0.02	0.04	0.02	0.02	0.06	0.08
β_2	0.1	0.08	0.1	0.12	0.12	0.16	0.16	0.08	0.08
β_3	0.1	0.1	0.1	0.1	0.12	0.14	0.16	0.16	0.14
β_4	0.1	0.1	0.02	0.12	0.1	0.14	0.04	0.12	0.12
β_5	0.42	0.46	0.42	0.5	0.42	0.5	0.5	0.5	0.5
β_6	0.42	0.5	0.42	0.48	0.42	0.42	0.5	0.5	0.48
β_7	0.44	0.48	0.42	0.46	0.42	0.44	0.5	0.5	0.5

In the above case, considering the floating ratio data of 9 kinds of situations in table 6, the interest increment of power grid enterprises and power generation units are calculated according to the different proportion of the net price, as shown at table 7 and table 8:

Table 7 Short term profit increment of each generating unit

Unit: thousand yuan

Subject	Increment of interests	Situations								
		1	2	3	4	5	6	7	8	9
Power generation unit 1	peak	6,620	8,765	8,765	6,620	8,765	6,620	6,620	10,910	13,056
	flat	-460	-460	-460	-460	-460	-460	-460	-460	-460

	valley	-1,822	-5,382	-5,382	-1,822	-5,382	-1,822	-1,822	-8,942	12,503
	total	4,337	2,922	2,922	4,337	2,922	4,337	4,337	1,508	93
Power generation unit 2	peak	692	183	692	1201	1201	2219	2219	183	183
	flat	682	682	682	682	682	682	682	682	682
	valley	-134	711	-134	-978	-978	-2,668	-2,668	711	711
	total	1,240	1,576	1,240	905	905	233	233	1,576	1,576
Power generation unit 3	peak	115	115	115	115	1,113	2,111	3,109	3,109	2,111
	flat	1,677	1,677	1,677	1,677	1,677	1,677	1,677	1,677	1,677
	valley	1,317	1,317	1,317	1,317	-340	-2,000	-3,653	-3,653	-2,000
	total	3,109	3,109	3,109	3,109	2,450	1,791	1,133	1,133	1,791
Power generation unit 4	peak	2,853	2,853	-1,428	3,923	2,853	4,994	-358	3,923	3,923
	flat	1,056	1,056	1,056	1,056	1,056	1,056	1,056	1,056	1,056
	valley	-2,035	-2,035	5,070	-3,812	-2,035	-5,588	3,293	-3,811	-3,811
	total	1,873	1,873	4,697	1,167	1,873	46.1	3,991	1,167	1,167
Power generation unit 5	peak	1,332	1,431	1,332	1,530	1,332	1,530	1,530	1,530	1,530
	flat	-62	-62	-62	-62	-62	-62	-62	-62	-62

	valley	-917	-985	-917	-1,054	-917	-1,054	-1,054	-1,054	-1,054
	total	353	384	353	414	353	414	414	414	414
Power generation unit 6	peak	1,093	1,205	1,093	1,177	1,093	1,093	1,205	1,205	1,177
	flat	-128	-128	-128	-128	-128	-128	-128	-128	-128
	valley	-951	-1,028	-951	-1,009	-951	-951	-1,028	-1,028	-1,009
	total	14	48	14	40	14	14	48	48	40
Power generation unit 7	peak	2,110	2,259	2,035	2,184	2,035	2,110	2,333	2,333	2,333
	flat	-102	-102	-102	-102	-102	-102	-102	-102	-102
	valley	-1,473	-1,576	-1,422	-1,524	-1,422	-1,473	-1,627	-1,627	-1,627
	total	535	580	512	557	512	535	603	603	603

Table 8 Short term profit increment of Power Grid Unit: thousand yuan

Short-term benefit	Incremental	Situations								
		1	2	3	4	5	6	7	8	9
Power Grid	Incremental revenue	78,890	78,990	78,990	78,990	78,990	78,990	78,990	78,990	78,990
	Incremental cost	77,078	76,109	78,463	76,146	74,646	73,403	76,377	72,067	71,302
	Incremental profit	1,912	2,881	527	2,844	4,344	5,587	2,613	6,923	7,688

(2)To maximize the benefit of generating units as the optimize target

Taking power generation unit 1 as an example, according to table 7, to calculate the maximum benefit of generating unit 1 is to search the situation where the maximum incremental profit of some power generation unit exists from the 9 situations listed at table 7. The analysis of the situations that taking one power generation unit as the subject at a time whose incremental profit was maximized are as following:

From the data in table 7, power generation unit 1 gets its maximum incremental profit in situations 1, 4, 6, 7, each of them is 4337 thousand yuan. In the context of the situation 1, all of the peak valley TOU tariff of all kinds of power generation units are listed in table 9:

Table 9 optimal TOU tariff when unit 1 profit maximum

Unit: yuan/kWh

Tariff	Peak	Flat	Valley
Power generation unit 1	0.368628	0.3614	0.352726
Power generation unit 2	0.45782	0.4162	0.366256
Power generation unit 3	0.46772	0.4252	0.374176
Power generation unit 4	0.42592	0.3872	0.340736
Power generation unit 5	0.481948	0.3394	0.268126
Power generation unit 6	0.628208	0.4424	0.349496
Power generation unit 7	1.0512	0.73	0.5694

(2)To maximize the benefit of power grid as the optimize target

To maximize the benefit of power grid as the optimize target, the calculating and analyzing methods are similar with that under the target where the benefit of power generation units were maximized. From the data in table 8, power grid had a maximum incremental profit in situation 9, which is 7688 thousand yuan. The TOU tariff of all the power generation unit of situation 9 are listed in table 10:

Table 10 the optimal TOU tariff when power grid profit maximum

Unit: yuan/kWh

Tariff	Peak	Flat	Valley
Power generation unit 1	0.390312	0.3614	0.326706
Power generation unit 2	0.449496	0.4162	0.376245
Power generation unit 3	0.484728	0.4252	0.353766
Power generation unit 4	0.433664	0.3872	0.331443
Power generation unit 5	0.5091	0.3394	0.25455
Power generation unit 6	0.654752	0.4424	0.336224
Power generation unit 7	1.095	0.73	0.5475

CONCLUSION

In this paper, considering the current situation of the integration of power trade in china, under the implementation of peak valley TOU tariff, the cost and profit of the users and the power grid, the power grid and the power generation unit were analyzed, the effect from the implementation of TOU tariff was studied. The Short –term and Long-term social costs of demand side and generation side were defined, and the mathematical meaning of the minimum of them were explained. Based on this, the quantitative relations between TOU tariff and each social cost. According to certain interest- distribution principals, the peak valley TOU tariff linkage optimization model was improved, therefore a scientific and feasible method to design demand-generation side linkage peak valley TOU tariff was provided.

Example simulation further verifies the feasibility of the model proposed in this paper. Under the vertical integration of China's current electricity trading system, changes in the cost of power generation side and the corresponding changes in the benchmark prices can not directly cause the demand response of end users, which is, in the economic sense, not the performance of resource allocation efficiency. On March 2015, China's State Council has issued A Number of Opinions on Further Deepening the Reform of the Electric Power System, the document has been clear to break the monopoly, to introduce direct competition in power generation and the sale of electricity, to independent account the transmission and distribution price of power grid, and the power grid should not directly involved in electricity trade. This shows that China's future electricity market reform direction has been basically clear, China's future energy efficiency is bound to be greatly strengthened.

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