Interaction of Energy-Grid-Load Based on Demand Side Response of Full-cost Electricity Price

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Abstract

In the research of intelligent grids, people usually pay attention to the interaction between power source and load to absorb more new energy. In contrast, the utilization of power source and load on grid resources is less considered, and energy-grid-load is not fully explored. The profound benefits and value of the three interactions. To this end, the paper proposes the interactive mode and method of power supply, power grid, and load based on full-cost electricity price. The power source side needs to consider the impact of transmission costs when optimizing economic dispatch; the load side needs to calculate the full-cost electricity price based on the power flow tracking method, clarify the load's use of power and grid resources, and reflect the "who benefits, who bears the cost" Principles and introduce demand-side response to reflect the meaning and value of full-cost electricity prices. The research found that the calculation example analysis based on the IEEE30-node system verifies that the method in this paper can reasonably allocate the cost of the power grid according to the user's utilization of power grid resources, thereby improving

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the efficiency, fairness, orderliness and safety of power grid investment and operation.

Keywords: Safe economic dispatch, power flow tracking, full-cost electricity price, demand-side response, energy-grid-load interaction.

1 Introduction

With the development of smart grids, people's focus has focused on the economic dispatch of energy-load interaction to absorb more new energy generation while often neglecting another interactive benefit of intelligent grids, that is, sharing the power grid reasonably. The economic dispatch of energy-grid-load interaction guided by node electricity price formed at the total cost. Energy-grid-load interaction is one of the main characteristics of the development of smart grids. However, the current electricity price system does not carefully consider grid resource utilization by power sources and loads. It is difficult to guide the rational layout of loads in time and space [1]. The transmission pricing mechanism under the grid monopoly operation mode is cost plus a reasonable profit.

In contrast, the current grid dispatching method does not consider the impact of grid fixed costs on power generation plans. The resulting trend can only be the full use of grid investment, and it isn't easy to judge grid investment. The rationality of this mechanism is easy to stimulate the impulse of power grid companies to invest. On the other hand, if short-term economic dispatch does not consider the fixed cost of transmission but only distributes the fixed cost of transmission evenly in the price of electricity sold, it will distort the nodal electricity price signal. More importantly, the current electricity price mechanism does not reflect the principle of "who benefits, who bears the cost," and there is unfairness in allocating transmission costs. Suppose the transmission price mechanism cannot reflect the difference in the cost of electricity consumption by users at different locations. In that case, this price mechanism is distorted and will lead to disorder, risk, and unfairness. Therefore, it is urgent to study an electricity price mechanism that apportions the total cost of the power grid according to the utilization of power and load to the grid resources to guide the reasonable distribution of power and load at the time and space scale, save power grid investment, suppress investment impulse, and reduce transmission grid loss. Encourage demand-side response and improve the overall safe and stable operation of the power grid.

This article summarizes the research status at home and abroad from two aspects: electric energy pricing and transmission cost allocation. The difference in node electricity prices is mainly caused by line congestion and network losses, without considering fixed transmission costs. In grid operation and planning, transmission costs account for a large proportion. The marginal transmission revenue recovered from node electricity prices alone cannot compensate for the total transmission costs. So, people began to study the consideration of transmission costs in node electricity prices [2]. Some scholars calculated the node marginal electricity prices based on the primal-dual interior-point method that disturbed the KKT condition and superimposed the fixed cost of line transmission to generation and load according to the power flow tracing method. Nodes from different node electricity prices. Some scholars have proposed a marginal cost pricing method of “net embedded” that comprehensively optimizes marginal costs for power generation and transmission and calculates the marginal electricity price considering the transmission cost. Some scholars have proposed a transmission pricing method suitable for China based on the British NETA pricing method. Based on this research background, this paper proposes an energy-grid-load interaction model based on full-cost electricity prices.

2 Source-network-load Interaction Model Based on Full-cost Electricity Price

This paper proposes an energy-grid-load interaction model based on full-cost electricity prices. The process is as follows. The first step is to consider the impact of transmission costs on the power generation plan in the traditional economic dispatch model, thereby forming a power flow result that considers the degree of utilization of power grid resources. In the second step, based on the power mentioned above, we use the power flow tracking method to allocate the grid’s fixed cost to each node to form a significant difference in the full-cost electricity price [3]. The third step is to calculate the load’s demand-side response to the full-cost electricity price; iterate in this way until the power generation plan converges.

2.1 Economic Dispatch Considering Transmission Cost

The optimization goal of traditional economic dispatch is to minimize the cost of power generation. In this dispatch mode, the units will generate power from low too high in the order. Power plants far away from the load centre have low unit power generation costs, but the power grid pays higher transmission costs. However, the unit power generation costs of power plants in the load centre are high. The power grid pays lower transmission costs for this purpose. It can support the safe and stable operation of the power grid. Traditional economic dispatching does not consider the impact of fixed transmission costs on power generation plans, and the resulting grid tidal flow conceals the effectiveness of grid investment [4]. Therefore, this article proposes a new economic dispatch model that considers transmission costs. Increase the transmission cost in the objective function of economic dispatch. The coefficient of the objective function of generator output is constantly updated with the change of the network flow, and the power generation plan becomes more reasonable. The power source should bear the transmission cost, and the load reasonably is considered. The power source and the grid the load interacts based on this actual cost, thus forming a trend that reflects the total cost.

2.2 Total Cost Electricity Price

The current node electricity price system does not apportion the transmission cost according to the extent to which it uses the grid resources. When the DC power flow does not consider the net loss and the line is not blocked, there is no difference in each node's electricity price, and it cannot reflect the impact of the transmission cost on the power and load time and space distribution.

The full-cost electricity price defined in this article includes the total cost of power generation and the full cost of transmission. The entire cost of power generation includes fixed costs and variable costs. For fixed costs, they are converted to each kilowatt-hour of electricity. We add the two parts of the cost to form the total cost of power generation; the total cost of transmission also includes fixed costs and variable costs. Under the model of considering DC power flow, variable transmission costs are not considered for the time being. The paper uses the power flow tracking method to reasonably allocate the power generation cost and the transmission cost to each node to differentiate the full-cost electricity price [5] significantly. When the flow changes, the full-cost electricity price is also revised accordingly, and the fairness and accuracy of the full-cost allocation are always maintained. The value of the full-cost electricity price is embodied in the following two aspects: 1. Different electricity prices will be generated for a single load when the operating state of the grid changes. It will accurately reflect the changes in the utilization degree of the load on the grid. 2. The full-cost electricity price gradually increases as the proportion of high-cost generator sets increases, which can better guide power investment and stimulate a demand-side response.

3 Full-cost Electricity Price Based on Power Flow Tracking

To allocate the cost of power generation and transmission to each node fairly and reasonably, this paper adopts the method of power flow tracing to carry out theoretical derivation and forms the full-cost electricity price. The power flow tracking method assumes that the incoming flow is entirely integrated. The outgoing flow strictly follows the principle of proportional sharing, ensuring the fairness of cost allocation and studying the flow of power sent or received by market participants in the network. This method can clarify the power corresponding relationship of each pair of power generation-load node pairs and clarify the topological distribution factor of the node and the line [6]. Simultaneously, the distribution ratio reflected by the topological distribution factor is always a non-negative value, avoiding negative power flow to cost allocation. The problems brought by. Since the network matrix representation form of the power flow tracking method has the advantages of clear form, analytical expression, and precise physical meaning, this article uses the matrix form to carry out the corresponding derivation and calculations. Suppose the system has n nodes and m lines in total.

3.1 The Power Generation Cost Component in the Full-cost Electricity Price

For node i, there is a node injection power balance equation:

$$P_i = \sum_{j \in a_i^u} |F_{ij}| + P_{Gi} \tag{1}$$

In the formula: a_i^u is the set of upstream nodes of node i; P_i is the total flowing power of node i (that is, the sum of generator power and upstream node inflow power); P_{Gi} is the generating power of node i; F_{ij} is the power flow of ij the line. In a lossless network, if $|F_{ij}| = |F_{ji}|$ is written $|F_{ij}|$ as $\frac{|F_{ji}|}{P_j} P_j$, then the formula (1) can be written as:

$$P_i - \sum_{j \in a_i^u} \frac{|F_{ji}|}{P_j} P_j = P_{Gi} \tag{2}$$

Write formula (1) in matrix form:

$$A_u P = P_G \tag{3}$$

In the formula: P is the node injected power vector; P_G is the node generated power vector; matrix A_u reflects the downstream distribution of the tidal current, which is called the downstream tracking matrix, and the elements in the ith row and jth column of A_u are:

$$[A_u]_{ij} = \begin{cases} 1, & i = j \\ -|F_{ji}|/P_j, & j \in a_i^u \\ 0, & \text{other} \end{cases} \tag{4}$$

When A_u is reversible, the node injects the power vector $P = A_u^{-1} P_G$. To unify the subsequent symbols, the paper uses k as the node subscript, and the kth element of the vector is expressed as:

$$P_k = \sum_{i=1}^{n} [A_u^{-1}]_{ki} P_{Gi} \tag{5}$$

Equation (5) reflects the contribution of all power generation nodes in the network to the injected power of the k node. According to the principle of proportional sharing, each power generation node contributes to the load power of the k node.

$$P_{Lk} = \frac{P_{Lk}}{P_k} \sum_{i=1}^{n} [A_u^{-1}]_{ki} P_{Gi} \tag{6}$$

Equation (6) reflects the contribution of generator power to the power of load node k in the network. From this, the unit power generation cost component (G_{UGk}) of the total cost electricity price of load node k can be derived. The process is as follows:

$$G_{TotalGk} = \frac{P_{Lk}}{P_k} \sum_{i=1}^{n} ([A_u^{-1}]_{ki} P_{Gi} C_{Gi}) \tag{7}$$

$$G_{UGk} = \frac{G_{TotalGk}}{P_{Lk}} \frac{1}{P_k} \sum_{i=1}^{n} ([A_u^{-1}]_{ki} P_{Gi} C_{Gi}) \tag{8}$$

In the formula: $G_{TotalGk}$ represents the total power generation cost that node k needs to bear; G_{UGk} represents the unit power generation cost of the full-cost electricity price of node k; C_{Gi} represents the unit power generation cost of power generation node i (including fixed costs and variable costs).

3.2 Transmission Cost Component of Full-cost Electricity Price

Corresponding to Section 3.2, for node i, there is a node power outflow balance equation:

$$P_i = \sum_{j \in a_i^d} |F_{ij}| + P_{Li} \tag{9}$$

P_i is the total injected power of the node; P_{Li} is the load power of the node; a_i^d is the downstream node set of nodes i; F_{ij} is the power flow of line E. We can derive the counter current tracking equation:

$$A_d P = P_L \tag{10}$$

P is the node outflow power vector; P_L is the node load power vector; matrix A_d reflects the upstream distribution of the tidal current, which is called the upstream tracking matrix, and the elements in the ith row and jth column of A_d are:

$$[A_d]_{ij} = \begin{cases} 1, & i = j \\ -|F_{ji}|/P_j, & j \in a_i^d \\ 0, & \text{other} \end{cases} \tag{11}$$

When A_d is reversible, a node injects the power vector $P = A_d^{-1} P_L$, and the ith element of the vector is expressed as:

$$P_i = \sum_{k=1}^{n} [A_d^{-1}]_{ik} P_{Lk} \tag{12}$$

For the flow on line ij, there are:

$$F_{ij} = \frac{F_{ij}}{P_i} P_i = \frac{F_{ij}}{P_i} \sum_{k=1}^{n} [A_d^{-1}]_{ik} P_{Lk} = \sum_{k=1}^{n} \frac{F_{ij}}{P_i} [A_d^{-1}]_{ik} P_{Lk} \tag{13}$$

Note that the physical meaning of $\frac{F_{ij}}{P_i}[A_d^{-1}]_{ik}$ in Equation (13) is the contribution of load node k to the power flow of the line. We can deduce the unit transmission cost component (C_{UTk}) of the total cost electricity price of load node k. The process is as follows:

$$C_{TotalTk} = \sum_{ij} \left(\frac{F_{ij}}{P_i} [A_d^{-1}]_{ik} P_{Lk} C_{Tij} \right) \tag{14}$$

$$C_{UTk} = \frac{TC_{Tk}}{P_{Lk}} = \sum_{ij} \left(\frac{F_{ij}}{P_i} [A_d^{-1}]_{ik} C_{Tij} \right) \tag{15}$$

In the formula: $C_{TotalTk}$ represents the total transmission cost that node k needs to bear; C_{UTk} represents the unit transmission cost of the full-cost electricity price of node k; C_{Tij} represents the unit transmission cost of the line.

3.3 Full-cost Electricity Price

The full-cost electricity price is defined as the linear superposition of power generation costs and transmission costs. After a unified subscript, there are:

$$\begin{aligned} C_{Uk} &= C_{UGk} + C_{UTk} \\ &= \frac{1}{P_k}\sum_{i=1}^{n}([A_d^{-1}]_{ki}P_{Gi}C_{Gi}) + \sum_{ij}\left(\frac{F_{ij}}{P_i}[A_d^{-1}]_{ik}C_{Tij}\right) \end{aligned} \tag{16}$$

The full-cost electricity price includes power generation cost and transmission cost components [7]. According to the power flow tracing method, the power grid's total cost is apportioned, reflecting the difference in the utilization of the power grid due to the different spatial distribution of loads, and thus bears the differentiated power generation and transmission costs.

4 Energy-grid-load Interaction Model Based on Full-cost Electricity Price

Based on the definition of full-cost electricity price in Section 3, a mathematical model of energy-grid-load interaction based on full-cost electricity price is established. The objective function is expressed as

$$\min \sum_{k=1}^{n} C_{Gk}P_{Gk} + \sum_{ij} C_{Tij}|F_{ij}| \tag{17}$$

The constraints are expressed as

(1) Power generation-load balance constraint

$$\sum_{k=1}^{n} P_{Gk} = \sum_{k=1}^{n} P_{Lk} \tag{18}$$

(2) The upper and lower limits of generator output

$$P_{Gk,\min} \leq P_{Gk} \leq P_{Gk,\max} \tag{19}$$

In the formula: In the formula: A corresponds to the upper and lower limits of the output of the generator set k.

(3) Limit constraints of line power flow corresponds to the upper and lower limits of the output of the generator set k.

(4) Limit constraints of line power flow

$$-F_{ij,\max} \leq F_{ij} \leq F_{ij,\max} \tag{20}$$

$F_{ij,\max}$ is the active power transmission limit of the line ij.

(5) Restrictions on the relationship between line power flow and distribution factor of the power output transfer

$$F_{ij} = \sum_{k=1}^{n} G_{ij-k}(P_{Gk} - P_{Lk}) \tag{21}$$

Where: G_{ij-k} is the distribution factor of generating transfer from unit k to the line ij.

(6) Full-cost electricity price constraints
According to the derivation of the full-cost electricity price in Section 2, the full-cost electricity price constraints can be obtained as follows:

$$\begin{aligned} C_{Uk} = \frac{1}{P_k} & \sum_{i=1}^{n}([A_d^{-1}]_{ki} P_{Gi} C_{Gi}) \\ & + \sum_{\text{All routes } ij} \left(\frac{F_{ij}}{P_i} [A_d^{-1}]_{ik} C_{Tij} \right) \end{aligned} \tag{22}$$

(7) Demand-side response function

$$P_{Lk} = f(C_{Uk}) \tag{23}$$

The formula $f(C_{Uk})$ is the demand response function of load node k, and different forms of functions can be used as needed. To simplify the analysis, this paper adopts the linear response function. Equation (22) includes power generation cost and transmission cost. Because the line power flow controlled by the transfer distribution factor will have a negative value, the line power flow's absolute value is introduced in the transmission cost item to ensure the correctness of the transmission cost calculation.

5 Feasibility Analysis of Energy-grid-load Interaction Based on Full-cost Electricity Price

5.1 Full-cost Electricity Prices Apply to Regulatory and Market Models

This paper's research content applies to both the government pricing environment and the electricity market environment. Its core idea is to allow the load to bear the corresponding total transmission cost according to the degree of utilization of the grid resources by the load, reflecting the "who benefits and who bears the cost" in principle [8]. At present, the node price does not consider the fixed cost of transmission, which distorts the node price signal.

5.2 The Executive Body of the Interactive Mode

The interactive mode is designed for the power generation and consumption plan of the power grid dispatching department. The supervisory department is responsible for formulating rules for the dispatch model that considers the total transmission cost. The supervisory department is the legislative body; the dispatching department performs dispatching following the rules. The dispatching department is the law enforcement agency and can consider the interests of the grid company.

5.3 Short-term Operation of the Power Grid Guides Long-term Investment Mechanism

Only when fixed costs are considered in the short-term can the power grid's long-term investment be scientifically guided by the short-term power flow distribution and price signals. The traditional short-term economic dispatch does not consider the fixed cost of transmission. On the one hand, if the fixed cost of transmission is evenly distributed to users by the stamp method, it will be unfair to users close to the power source. On the other hand, if the fixed cost of transmission is based on the trend of traditional economic dispatch, it will be unfair [9]. The power flow tracking method is also unfair to share the transmission cost because users passively accept the expensive transmission price. If power plants close to users generate more power, they can avoid the cost of long-distance transmission.

Under the premise of demand elasticity, the traditional economic dispatch model's objective function is to minimize the cost of power generation. Its purpose is to maximize the social welfare formed by power generation and users. However, the decision-making trend does not consider the impact of transmission costs. The trend results from a lack of fairness; this model's goal is to minimize the total cost of power generation and transmission. Although the variable cost of short-term dispatch operation is slightly increased, its decision-making trend is related to the reasonable allocation of fixed costs, which reflects "who benefits," who the basic principle of the economics of "undertaking," resulting trend reflects the effectiveness of investment.

In the interactive mode proposed in this article, the utilization rate of transmission lines may be reduced in the short term, which means that the payback period of power grid investment costs may become longer. Still, it will have a profound impact on guiding the saving of power grid investment and construction costs in the long term. It only passively bears the cost caused by the unreasonable investment of the power grid. Still, through the response to the full-cost electricity price, feedback influences the power grid investment planning decision and saves the power grid investment to produce more effective social welfare.

5.4 Full-cost Electricity Prices Help Prevent Grid Congestion

Under the traditional node electricity price mechanism, each node's electricity price is the same before the grid is blocked, and it is difficult to guide users' electricity consumption behaviour [10]. Under the full-cost electricity price mechanism, since a load of nodes farther from the power generation centre will bear more fixed costs of transmission, the electricity price of these nodes will inevitably increase, which will effectively encourage a load of these nodes to be redistributed in time sequence and realize the shift. Peaks fill valleys; in the long run, high node electricity prices will stimulate the spatial transfer of loads, reducing the flow of long-distance transmission lines. Therefore, compared with traditional node electricity prices, the full-cost electricity price mechanism helps prevent grid congestion.

6 Solution Method of Energy-grid-load Interaction Model Based on Full-cost Electricity Price

6.1 Eliminate the Nonlinearity of the Objective Function

According to Section 4, the objective function Equation (17) of the model is a nonlinear function with absolute value. To ensure the model solution's efficiency, the nonlinearity of the objective function needs to be eliminated first. The items with absolute values in the objective function are all lines of $\sum_{ij} C_{Tij}|F_{ij}|$. For any line, the nonlinearity caused by the absolute value can be eliminated according to the following method:

(1) Introduce auxiliary variableu_{ij}, v_{ij}:

$$u_{ij} = C_{Tij}\frac{|F_{ij}| + F_{ij}}{2} \tag{24}$$

$$v_{ij} = C_{Tij}\frac{|F_{ij}| + F_{ij}}{2} \tag{25}$$

u_{ij}, v_{ij} satisfies:

$$u_{ij} + v_{ij} = C_{Tij}|F_{ij}| \tag{26}$$

$$u_{ij} - v_{ij} = C_{Tij}F_{ij} \tag{27}$$

(2) The objective function becomes:

$$\min \sum_{k=1}^{n} C_{Gk}P_{Gk} + \sum_{ij} u_{ij} + v_{ij} \tag{28}$$

(3) Introduce linear auxiliary constraints:

$$\begin{cases} C_{Tij}F_{ij} - u_{ij} + v_{ij} = 0 \\ u_{ij} \geq 0, v_{ij} \geq 0 \end{cases} \tag{29}$$

6.2 The Interactive Model Solution Process

Since the full-cost electricity price constraint formula (29) contains forward and reverse flow matrices A_u and A_d perform inverse calculations, the denominator of the matrix elements contains variables, and this constraint has strong nonlinearity; and when the direction of the power flow of the entire network changes, the matrix position of the element in the middle will change. Based on the above two reasons, the model is challenging to optimize and solve in a unified way.

The steps to solve the model are as follows: (1) Set the initial load value and system network boundary conditions. (2) Use the linear programming solution tool to calculate the economic dispatch considering the transmission cost. (3) According to the results of economic dispatching power generation and line power flow, calculate the power generation cost and transmission cost

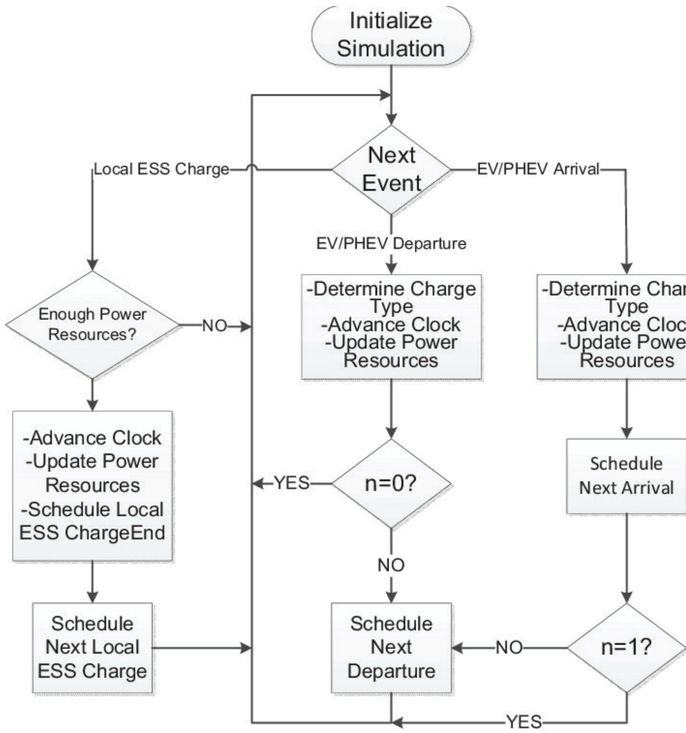

Figure 1 Algorithm solution flowchart.

allocation based on power flow tracking to form the full-cost node electricity price. If the convergence condition is met, the difference between the full cost electricity price of each node in the two calculations is less than the threshold (skip to step 6); if the convergence condition is not met, skip to step (4). (4) The node load makes a demand-side response to the full-cost node electricity price. (5) Use the response load as the new initial load value and skip to step (2). (6) The calculation is over. The solution process is shown in Figure 1.

7 Example Analysis

This paper adopts the network parameters and structure of the IEEE30-node standard system. The unit power generation cost of the unit and the unit transmission cost data considering the transmission line's length refer to the actual data of a particular regional power grid in China [11]. Due to the iterative solution method, the demand-side response function can take different forms of functions. To simplify the analysis, this article uses the linear response function as follows:

$$P_{Lk} = -a_k C_{Uk} + b_k \tag{30}$$

The formula: a_k is 0.005; b_k is the initial value of the IEEE-30 node standard system load.

7.1 Comparison of Economic Dispatch

Table 1 Compares the results of traditional economic dispatch and economic dispatch in this paper. It can be seen from Table 1 that traditional economic dispatch does not consider the impact of transmission costs and only generates electricity according to the unit power generation cost from low to high; however, the method in this paper can carefully consider the usage of the generator set on the network when making dispatching decisions, while The introduction of nonlinearity in the objective function makes the coefficient of power generation in the objective function formula (29) update continuously with the changes of the network power flow, making the power generation plan more reasonable.

The method in this paper takes into account the impact of transmission cost. From Table 2, it can be seen that the total transmission cost has dropped significantly by 39.1%. The traditional method does not consider the impact of transmission costs in operation, and the resulting flow is the full use of the power grid. Still, it cannot reflect the effectiveness of power grid investment. This paper considers the optimal utilization of transmission resources and evaluates the effectiveness of grid investment from the overall perspective.

Table 1 Power output comparison of generator sets

Power Generation Node	Traditional Economic Dispatch/MW	Method of this Paper/MW
1	0	29.233
2	0	0
5	83.4	100
8	0	31.624
11	100	85.251
13	100	37.292

Table 2 Comparison of total transmission cost and line flow

Algorithm	Total Transmission Cost/Yuan	Total Line Power Flow/MW
Traditional economic dispatch	12 074.55	674.461
Economic dispatch	7 352.56	429.719

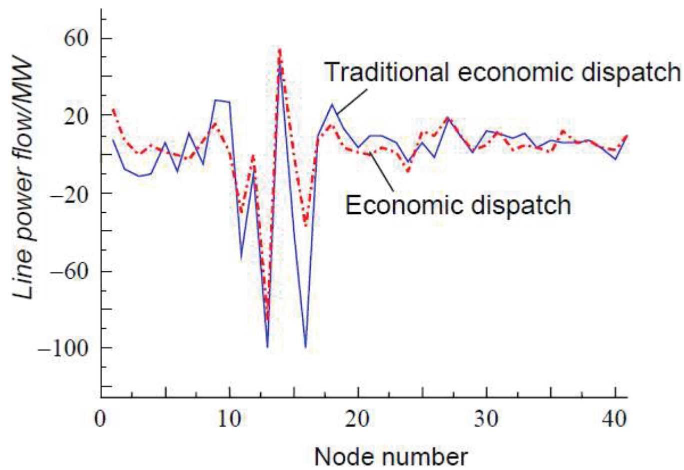

Figure 2 Line power flow comparison chart.

It can be seen from Figure 2 that the power flow of each line has a different rate of decline. The power flow of lines 1, 25, 36, etc., when the trend of the whole network shows a sharp decline, the power flow of the line is increased, and the decline of the line is slight, or the increase of the line is significant. Some are concentrated in the power generation centre. The lines with a significant decline are distributed in the area far away from the power generation centre, reflecting the effect that the method in this paper can meet the load demand nearby.

7.2 Comparison of Demand Response Results of Different Transmission Cost Allocation Methods

This article discusses the following two methods: (1) Method 1: Electricity price response method based on stamp method. (2) Method 2: Full-cost electricity price response method based on power flow tracking (the method in this article). A comparison was made, and the results are shown in Table 3.

Table 3 Comparison of total network load

Method	Total load/MW
Method 1	243.17
Method 2	240.425

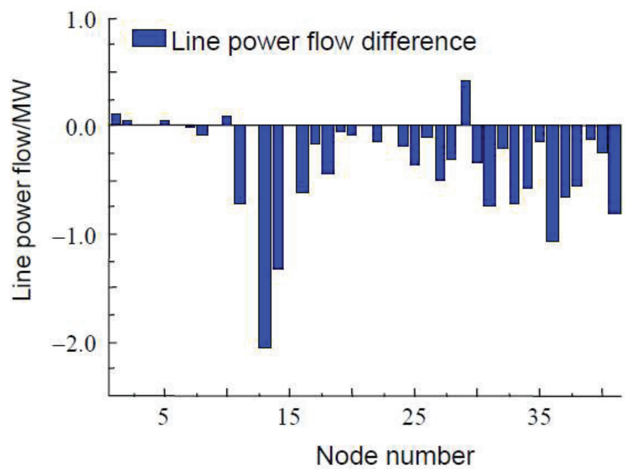

Figure 3 Trend tracking method-stamp method line tidal current difference map.

It can be seen from Table 3 that compared with the response result of Method 1; the total load of Method 2 is reduced by 2.76%. Figure 3 shows the power flow comparison of the two methods. The figure shows method two minus the line power flow difference of method 1. It can be seen from the figure that the tide of most lines has dropped significantly, reflecting the downward trend of the overall tide. Some lines close to power generation nodes, such as lines 1, 2, 10, 19, 24, 29, etc., are reflected in the relative decrease in overall load, and the results of method 2 are lower than those of method 1 for some lines. The phenomenon of increased tidal current indicates that the tidal current is not uniformly decreasing. The routes far away from the power generation centre, such as routes 13, 33, 41, etc., significantly decrease the tidal current [12]. The above results reflect that the demand-side response based on the full-cost electricity price has redistributed the power flow of the entire network. The power flow of the remote line is shifted to the line close to the power generation centre. The power flow has a phenomenon of “near big and far small.”

Figure 4 shows the impact of the two methods on the load. Observation shows that the load difference between the two methods is negligible at load

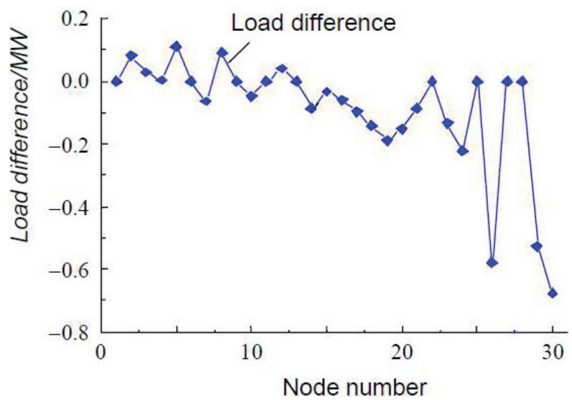

Figure 4 Graph of response node load difference based on tidal current tracking method-stamp method.

nodes close to the power generation centre. Some nodes have higher loads after responding based on full-cost electricity prices. For the load nodes far away from the power generation centre, Method 2 enables these nodes to share higher transmission costs, so the load is significantly reduced, reflecting that the method in this paper achieves a reasonable spatial distribution of loads.

It can be seen from Table 4 that the full-cost electricity price based on power flow tracking has increased significantly at nodes far away from the power generation centre, reflecting the principle of "who benefits, who bears the cost." For nodes with a long distance between supply and demand, the shared cost is enormous. The full-cost electricity price considering the fixed cost of transmission has been significantly increased before the occurrence of congestion. Regarding Figures 2 and 3, the line power flow, especially the remote line, has decreased significantly. It is verified that this method has Conducive to prevent line blockage. It can be seen from Figure 4 that a load of nodes with more price increases after the demand side response has dropped significantly.

Combined with Figures 2, 3 and Table 4, the method in this paper considers transmission costs in both economic dispatch and full-cost electricity prices, reflects the actual demand of power generation sets and power users on the grid, and compares the return on investment of power transmission by grid companies to the comparison of power generation sets and power users. The combination of the utilization of the power grid promotes rational investment by power grid companies.

Table 4 Comparison of full-cost electricity prices

Node Number	Stamp Law/¥	Trend Tracking Method/¥	Node Number	Stamp Law/¥	Trend Tracking Method/¥
1	380	380	16	382.12	393.87
2	402.03	385.81	17	372.93	392.17
3	402.12	396.52	18	382.12	410.67
4	400.86	400.13	19	373.14	410.99
5	392.16	370.17	20	372.12	402.7
6	350	391.6	21	372.12	389.63
7	379.96	392.78	22	350	396.79
8	408.88	390.49	23	382.12	409.02
9	350	370.8	24	374.03	418.7
10	372.12	381.8	25	351.91	451.62
11	350	350	26	374.03	489.62
12	382.12	374	27	356.26	442.76
13	360	360	28	356.76	399.85
14	382.12	399.59	29	378.37	484.29
15	382.12	388.82	30	378.37	513.94

In summary, the energy-grid-load interaction method based on the full-cost electricity price embodies the principle of "who benefits, who bears the cost." After users respond based on the new electricity price, the entire network's power flow can be reduced, and the power flow of the line will be reduced. The remote nodes and lines are transferred to the nodes and lines close to the power generation centre. The load layout is reasonably distributed to encourage the interaction between the power source and the power grid, and the load and the power grid, to guide the reasonable distribution of the load [13]. Simultaneously, for the nodes with a long distance between supply and demand, share the cost is relatively high, and the demand side response is used to reduce the flow of long-distance transmission lines and prevent line blockage, which is conducive to grid safety. The paper combines the return on investment of grid enterprises to utilize the power grid by units and users to guide rational investment in the grid.

8 Conclusion

This paper proposes an energy-grid-load interaction model and method based on the full-cost electricity price. The power flow tracking method is used to calculate the unit power generation cost and unit transmission cost of the node based on the economic dispatch of the transmission cost. The full-cost electricity price is formed. The full-cost electricity price responds to the demand side. It is expected that the academic thoughts in this article will have significant reference value for Chinese transmission and distribution price reform and market-oriented operation.

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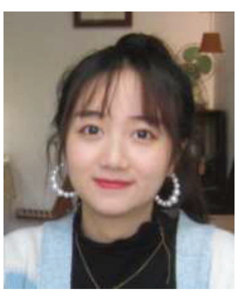
Biographies



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