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# A Transmission and Distribution Cooperative Congestion Scheduling Strategy Based on Flexible Load Dynamic Compensation Prices

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**Abstract:** With the demand response and the massive access of distributed energy to the distribution network, it is possible to solve the transmission congestion problem by coordinating the controllable resources in a transmission network and distribution network. Aiming at resolving the problems of scattered side response resources and difficult-to-negotiate compensation prices, a bi-level optimal congestion scheduling strategy based on flexible load dynamic compensation prices is proposed. Under this strategy, the transmission network layer aims at minimizing the congestion cost and optimizes the adjustment scheme of the generator set and the node price. The active distribution network layer obtains the dynamic compensation price of the flexible load of the distribution network through the load characteristics and the node price. Through the interaction and coordination between the two layers, an optimal congestion scheduling scheme is obtained, and the transmission and distribution jointly solve the congestion problem. Based on the modified IEEE-39 experimental system, the effectiveness of the proposed strategy is verified via a simulation.

**Keywords:** congestion management; transmission and distribution coordination; active distribution network; demand response; compensation price

## 1. Introduction

The traditional method of transmission congestion management is mainly to change the generator output or reduce the load; however, the congestion cost is high. With the development of smart grids, a large number of flexible and schedulable resources are connected to an active distribution network, which increases the controllability of the distribution network. Encouraging these controllable resources to participate in transmission network congestion management is environmentally friendly and reduces the congestion cost, which provides a new idea for transmission network congestion management. Therefore, it is of great significance to study the transmission and distribution of cooperative transmission network congestion management methods.

In the electricity market environment, the most direct way to eliminate congestion is to use a transmission congestion management mechanism to adjust or cut all kinds of transactions and rearrange the power generation plan [1–6]. Considering the influence of uncertain factors in the power system, the burden of generator rescheduling resources under transmission congestion is reduced to ensure the safe and economic operation of the power system. Reference [7] established a set of quantitative evaluation indexes to evaluate a transmission congestion management mechanism. In reference [8], a dayahead transmission congestion management model was constructed by using a chanceconstrained optimization method, which considered the influence of wind power, load,



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**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). and demand response uncertainty on transmission congestion management and improved the overall safety level of the system.

The traditional congestion management method is to adjust the output of the generator on the transmission side, which has high congestion management costs and poor economic consequences [9–11]. The thermal power unit on the transmission side uses coal and other combustibles to generate electricity, which increases carbon emissions and environmental pressure. In addition, although the thermal power unit has a large installed capacity and stable output, the regulation range is small, the climbing rate is low, the start-up time is long, and the flexibility adjustment ability is weak. Therefore, the traditional congestion management method has defects, and it does not fully dispatch all kinds of resources with a better economy, more friendly impact on the environment, and more flexible adjustment ability on the distribution network side.

With the development of active distribution networks, the types of flexible resources in distribution networks are constantly enriched, and the scale is increasing [12–16]. Flexible resources include controllable units, energy storage, new energy, and flexible loads. Flexible loads include interruptible loads, shiftable loads, and transferable loads. These flexible resources are small in capacity, large in quantity, and widely distributed. It is difficult to consider a single flexible resource. The method for integrating and utilizing flexible resources is an urgent problem to be studied.

A distribution network dispatching center can directly reduce the load of flexible power consumption or stimulate the load of flexible power consumption to spontaneously respond through price incentives to alleviate congestion. Reference [17] established an intraday spot market congestion optimization scheduling model to promote the consumption of renewable energy, which mobilized the "source-load" bilateral schedulable resources, reduced the congestion scheduling cost, and promoted the consumption of renewable energy. In reference [18], a bi-level optimization model of transmission and distribution coordination for a distribution network as a virtual power plant participating in congestion management in the electricity spot market was proposed. Virtual power plant technology was used to aggregate the schedulable resources of the distribution network to alleviate transmission congestion. Reference [19] proposed a bi-level optimal scheduling model with distribution network companies as the main bodies to participate in the congestion management of the electricity spot market. Considering the voltage fluctuation of the distribution network and the user response satisfaction, the ATC algorithm can be used to solve the upper and lower models. Reference [20] defined the generalized bidding function of the active distribution network and the external regulation margin as the coordination medium between the transmission and distribution network and used the sensitivity coefficient of the node to the line for congestion management to eliminate the line congestion. The above research does not consider the impact of load demand difference and load satisfaction on the compensation price and ignores the consideration of load-side participation in the coordination process.

Based on the characteristics of node price and load satisfaction, this paper proposes a bilevel optimal congestion scheduling strategy for transmission and distribution coordination based on the dynamic compensation price of flexible loads in a distribution network so as to maximize the utilization of the global resources of the power grid. The dynamic cooperative compensation method is used to solve the transmission congestion problem and reduce the congestion management cost.

The main contributions of this paper can be summarized as follows:

- The congestion management architecture and the process of transmission and distribution coordination are identified;
- The dynamic compensation prices of flexible loads are obtained based on load satisfaction;
- The model of the transmission network layer and distribution network layer is established, and the bi-level optimal congestion scheduling model of transmission and distribution coordination is obtained;

• Based on the modified IEEE-39 experimental system, the effectiveness of the proposed strategy is verified using a simulation.

The rest of this article is organized as follows: Section 2 summarizes the relevant background, ideas, and main framework. Section 3 introduces the solution of the transmission network, distribution network layer model, and two-layer model in detail. Section 4 is the simulation analysis of the example. Section 5 summarizes the work of this paper.

# 2. Transmission and Distribution Collaborative Congestion Management Architecture and Process

## 2.1. Congestion Problem and Compensation Price

In the day-ahead coordinated scheduling scheme of the transmission and distribution network, the power generation plan for the next 24 h was formulated according to the load forecasting, and the transmission capacity of the transmission network was not considered in the economic scheduling process. Before the market cleared, the power flow security check was carried out. The power flow of the transmission line may have exceeded the safe range, and line congestion may have occurred.

The traditional way is to adjust the output of the generator to solve the congestion problem, with a high cost. As shown in Figure 1, without considering the upper limit of the transmission capacity of line AB, the optimization calculation was carried out with the lowest cost as the goal. The quotation for the G1 generator was 300 yuan/MWh, and the quotation for the G2 generator was 500 yuan/MWh. The quotation for the G1 generator was low, and the upper limit of the output was greater than the total load. Therefore, G1 provided an output for all the loads, and the power generation of G1 was 1000 MW, of which the power supply to the load  $L_1$  was 400 MW. Additionally, the power supply to the load  $L_2$  was 600 MW. The load needed to be transmitted to node B through line AB, but the maximum transmission capacity of line AB was 400 MW therefore the branch power exceeded its maximum value. This meant line AB was blocked.



Figure 1. Analysis of two-node system congestion.

In order to solve the blocking problem of line AB, it was necessary to adjust the generator output. The maximum transmission capacity of line AB was 400 MW, and the output of generator G1 was reduced to 800 MW, in which the power supply to the load  $L_1$  was 400 MW, the power supply to the load  $L_2$  was 400 MW, and the output of generator G2 increased to 200 MW to supply power to the load  $L_2$ . Based on the generator quotation and power generation, the cost was calculated. The cost before the adjustment was 300,000 yuan, all of which was the cost of generator G1, and the adjusted cost was 340,000 yuan, of which the cost of generator G1 was 240,000 yuan and the cost of generator G2 was 100,000 yuan. According to the cost calculation before and after the adjustment, the blocking cost was 40,000 yuan.

According to the analysis, the reason for the transmission congestion was the conflict between the economic target and the line transmission capacity limit. Without considering the transmission capacity limit of the line, when the optimization was carried out with the lowest cost as the goal, the branch power of the line exceeded the upper limit value and congestion occurred. In order to solve the congestion situation, it was necessary to adjust the output of the generator and use more expensive units, resulting in increased costs.

Due to the large access of flexible resources in the distribution network, adjusting the load on the distribution network side could also solve the congestion problem. Assuming that the load  $L_2$  was all interruptible load, the interruption compensation price was 400 yuan/MWh. The price of generator G2 was 500 yuan/MWh. Compared with generator G2, the cost of load interruption was lower. The optimization calculation was carried out with the lowest cost as the goal. When the load  $L_2$  interruption was 200 MW, the load of node B became 400 MW, and the power generation of G1 was 800 MW. The power supply to the load  $L_1$  was 400 MW, the power supply to the load  $L_2$  was 400 MW, and the power of line AB did not exceed the maximum transmission capacity of 400 MW, and the blocking disappeared. According to the generator quotation and power generation, the load interruption, and the interruption compensation price, the cost was calculated. The adjusted cost was 320,000 yuan, of which the cost of generator G1 was 240,000 yuan, and the cost of interruption load compensation was 80,000 yuan. The cost before the adjustment was 300,000 yuan, and the blocking cost was 20,000 yuan.

Comparing the congestion costs of the two adjustments, it can be seen that the use of flexible resources with lower load-side prices can effectively reduce the congestion costs.

The interruption compensation price was reduced to 350 yuan/MWh, and the optimization calculation was carried out with the lowest cost as the goal. When the load  $L_2$ interruption was 200 MW, the congestion disappeared. The adjusted cost was 310,000 yuan, of which the cost of generator G1 was 240,000 yuan, and the cost of interruption load compensation was 70,000 yuan. The cost before the adjustment was 300,000 yuan, and the blocking cost was calculated to be 10,000 yuan. The congestion cost was lower when the interruption compensation price was reduced.

Reducing the compensation price reduces the total cost, but the compensation price cannot be excessively reduced, otherwise it will affect the enthusiasm of the load to participate in the demand response. Discovering how to determine a reasonable price range, not only to reduce costs, but also to ensure the enthusiasm of the response, is a problem that needs further consideration.

In this paper, the compensation price was obtained by using load satisfaction. This was achieved by using the influencing factors to obtain the satisfaction, then dividing the satisfaction range and calculating the compensation price. The higher the satisfaction, the lower the compensation price. Dividing the number of intervals of satisfaction is different, and the compensation price of reasonable-range dynamic change can be obtained.

The transmission and distribution coordination method was used to solve the congestion problem, and the load satisfaction was used to obtain the dynamic compensation price to reduce the congestion management cost.

#### 2.2. Dynamic Integration of Distribution Network Flexibility Resources

The flexibility resources of the distribution network were classified and integrated, including the controllable units, energy storage, new energy, and flexible load categories. The flexible load included interruptible loads, shiftable loads, and transferable loads.

The controllable unit was mainly a gas turbine, which relied on fossil fuel combustion to provide power. It had the characteristics of fast-response speed and a short start-stop time with high controllability. Energy storage equipment can utilize its own charging and discharging power, enabling two-way flow characteristics and flexible conversion between power supply and load, thus playing a role in peak load shifting. New energy mainly includes wind and photovoltaic power generation units, which are safe, clean, and rich in resources. Flexible loads include interruptible loads, shiftable loads, and transferable loads. The interruptible load type can be partially or completely reduced according to the need; the shiftable load type can be constrained by the production process, and only the overall shift of the power curve can be carried out. The total power consumption of the transferable load is constant in a scheduling cycle, but the power consumption of each period can be flexibly adjusted.

To change the load electricity consumption behavior, it is necessary to offer certain compensation to encourage participate in the demand response. In our study, the fixed ladder price was mainly implemented and the differentiation characteristics of various types of loads were not considered, which could not fully mobilize the enthusiasm of the demand response.

Considering the differences in the load characteristics and demand, the load law was counted and the dynamic step compensation price was obtained according to the load satisfaction characteristics.

The number of steps in the compensation price was dynamic. According to the number of dynamic steps, the interval was divided in the [0, 1] satisfaction range.

$$u_1 = \frac{n-1}{k_L^s} \ n \in [1, k_L^s] \ n \in Z$$
(1)

$$u_2 = \frac{n}{k_L^s} n \in [1, k_L^s] n \in \mathbb{Z}$$

$$\tag{2}$$

Among them,  $k_L^s$  is the number of dynamic steps,  $3 \le k_L^s \le 10$ .  $a_1$  is the first endpoint value of all the satisfaction intervals,  $a_2$  is the end-point value of all the satisfaction intervals, and n is the nth step.

The higher the satisfaction of load participation in the demand response, the lower the compensation price. According to the satisfaction degree from high to low, the dynamic relationship curve of the ladder compensation price is formed.

$$\lambda_L^s = \theta_L (1 - \alpha_L^s) \tag{3}$$

Among them,  $\lambda_L^s$  is the step compensation price,  $\theta_L$  is the sensitivity coefficient of load to satisfaction, and  $\alpha_L^s$  is the intermediate value of each satisfaction interval.

The electricity demand of the interruptible load mainly focuses on temperature, and the interruptible load affects the thermal comfort feeling [21]. The load is coordinated as a whole, and the overall distribution of satisfaction is obtained by data-driven methods.

When the temperature control load is not interrupted, the room temperature is kept at the most comfortable temperature. When the switch is turned off and the load is interrupted, the indoor temperature calculation formula is as follows:

$$\Gamma_{in}^{t} = T_{out}^{t} - (T_{out}^{t} - T_{0})e^{-\Delta t/RC}$$
(4)

Among them,  $T_0$  is the most comfortable temperature set,  $T_{out}^t$  is the outdoor temperature at t, R is the indoor equivalent thermal resistance, and C is the indoor equivalent heat capacity.

The internationally recognized thermal comfort evaluation model is the predicted mean vote (PMV) model proposed by Professor Fanger. The simplified calculation formula is as follows:

$$I_{PMV} = aT_{in} - c \tag{5}$$

Among them,  $I_{PMV}$  is the PMV index value, *a* and *c* are the known parameters, and  $T_{in}$  is the indoor temperature after the load is interrupted. When the calculated value of the PMV index is 0, the user is the most satisfied and the corresponding temperature value is the most comfortable temperature.

The calculation formula of satisfaction is:

$$\alpha_{IL} = \exp\left(-\left(0.03353 \times I_{PMV}^4 + 0.2179 \times I_{PMV}^2\right)\right)$$
(6)

Among them,  $\alpha_{IL}$  is the satisfaction of participation in the demand response.

According to the data-driven fitting, the probability density distribution curve of the overall satisfaction of the interruptible load is obtained. According to the number of dynamic steps, the interval is divided in the range of [0, 1] satisfaction, the interval probability is obtained using an integral, and the interruption power of each interval is calculated.

$$p = \int_{a_1}^{a_2} f(\alpha_{IL}) \, \mathrm{d}\alpha_{IL} \tag{7}$$

Among them, *p* is the probability obtained using the integration of the satisfaction interval,  $f(\alpha_{IL})$  is the probability density function of the satisfaction,  $a_1$  is the first endpoint value of all the satisfaction intervals, and  $a_2$  is the end-point value of all the satisfaction intervals.

According to the number of dynamic steps  $k_{IL}^s$ , the dynamic relationship curve between the load interruption power and the step compensation price is formed.

The power demand of the shiftable load mainly focuses on the power consumption period. The shorter the shift time, the lower the deviation from the original power consumption time, and the higher the load satisfaction.

The *i*th translatable load satisfaction calculation formula is as follows:

$$\alpha_{SL}^{i} = \frac{t_{\max} - \beta_{SL}^{i} (t_{SL0}^{i} - t_{0}^{i})}{t_{\max}}$$
(8)

Among them,  $t_{\text{max}}$  is the longest shiftable length,  $\alpha_{SL}^i$  is the satisfaction of the *i*th shiftable load,  $t_0^i$  is the original start time of power consumption,  $t_{SL0}^i$  is the start time of power consumption after translation, and  $\beta_{SL}^i$  is the correction coefficient, which is related to the length of load power consumption.

According to the number of dynamic steps  $k_{SL}^s$ , the dynamic relationship curve between the load satisfaction and step compensation price is formed, and the corresponding compensation price is obtained according to the satisfaction after load translation.

The electricity demand of the transferable load mainly focuses on the electricity consumption, which can be flexibly adjusted in each period. The smaller the total amount of load transfer, the higher the satisfaction.

The satisfaction calculation formula is as follows:

$$\alpha_{TL} = 1 - \frac{\sum_{t=1}^{I} |P_{TL}^{t}|}{\sum_{t=1}^{T} P_{TL0}^{t}}$$
(9)

Among them,  $P_{TL}^t$  is the transfer power at time t,  $P_{TL0}^t$  is the total amount of transferable load at time t, and  $\alpha_{TL}$  is the satisfaction of the load.

According to the number of dynamic steps  $k_{TL}^s$ , the dynamic relationship curve between the load satisfaction and step compensation price is formed, and the corresponding compensation price is obtained.

Using the characteristics of flexible load satisfaction, the dynamic step compensation method was used to compensate the load participation in the demand response, and the enthusiasm of participation was fully mobilized.

# 2.3. Congestion Management Architecture and the Process Considering Flexible Resource Participation

The transmission and distribution collaborative congestion management architecture with flexible resource participation is shown in Figure 2.



Figure 2. Transmission and distribution collaborative congestion management architecture.

As a controllable energy unit of the transmission network, the distribution network has various types of internal schedulable resources, complex operating characteristics, and a wide distribution. In order to reduce the difficulty of scheduling, regardless of the grid structure of the distribution network, the entire distribution network was connected to the upper transmission network as a whole through the transformer. The data collection and statistics of the internal resources were performed at the contact node, various types of flexible resources were classified according to the clustering, and the internal resources were scheduled through the distribution network scheduling center.

When the transmission line was blocked, the line monitoring device uploaded the blocking information to the transmission network dispatching center. At this time, the traditional power plant provided new bidding information to the power market. The transmission network dispatching center technically confirmed the market parameters and operating parameters and determined the adjustment scheme of each power plant with the lowest blocking cost. The node price of the contact node was obtained and the node price was sent to the distribution network control center. According to the price, the distribution network control center re-dispatched the internal resources through the dynamic collaborative compensation method to obtain the distribution network purchase power and reported it to the transmission network dispatching center. In this way, the information was continuously updated until the two-layer goal of the minimum transmission network was met, which meant the transmission congestion problem was finally solved. The specific solution process is shown in Figure 3.



Figure 3. Flow chart of transmission and distribution collaborative congestion management.

# **3.** Congestion Scheduling Model Based on Transmission and Distribution Coordination *3.1. Transmission Network Layer Model*

The transmission network layer takes the purchase power transmitted by the distribution network layer as the known condition. According to the quotation of each power plant, the adjustment scheme of the generator set was determined with the minimum increase in the purchase cost as the goal. The mathematical model is as follows:

Objective function:

$$\min\sum_{t=1}^{T}\sum_{i=1}^{N_{G}} \left[ f_{i}(P_{i}^{t})P_{i}^{t} - f_{i,o}(P_{i,o}^{t})P_{i,o}^{t} \right]$$
(10)

Among them, *T* is the total number of time periods,  $N_G$  is the number of units,  $P_i^t$  is the output of unit *i* after adjustment at time *t*,  $P_{i,o}^t$  is the output of unit *i* before adjustment at time *t*,  $f_i$  is the original quotation function of unit *i*, and  $f_{i,o}$  is the quotation function after blocking unit *i*.

The constraints are as follows:

The power balance constraints are as follows:

$$\sum_{i=1}^{N_G} P_i^t = P_d^t + P_B^t \tag{11}$$

Among them,  $P_d^t$  is the total load of the transmission network at time *t* except the distribution network nodes and  $P_B^t$  is the purchase of electricity for the distribution network at time *t*.

The upper and lower limit constraints of the generator output are as follows:

$$P_i^{\min} \le P_i^t \le P_i^{\max} \tag{12}$$

Among them,  $P_i^{\text{max}}$  and  $P_i^{\text{min}}$  are the upper and lower limits of the output for unit *i*. The climbing rate constraint is as follows:

$$P_{i}^{t-1} - DR_{i} \le P_{i}^{t} \le P_{i}^{t-1} + UR_{i}$$
(13)

Among them,  $UR_i$  and  $DR_i$  are the increase and decrease output limit for unit *i*. The branch power constraint is as follows:

$$\left|P_{ij}^{t}\right| \leq P_{ij}^{\max} \tag{14}$$

Among them,  $P_{ij}^t$  is the transmission power of the line between node *i* and node *j* of the transmission network at time *t* and  $P_{ii}^{max}$  is the maximum transmission power of line *ij*.

The branch power flow can be calculated by using the *T* matrix, namely the power transfer distribution factor (PTDF).

The following formula is used to calculate the DC power flow:

$$P_{node} = B_0 \theta$$

$$P_{i-j} = \frac{\theta_i - \theta_j}{x_{ii}}$$
(15)

Among them,  $P_{node}$  is the active power vector injected into all the nodes except the balanced nodes,  $\theta$  is the node voltage phase angle vector,  $B_0$  is the node admittance matrix,  $P_{i-j}$  is the active power flow of the branch ij,  $\theta_i$  and  $\theta_j$  are the voltage phase angles of node i and node j, and  $x_{ij}$  is the reactance of branch ij.

$$P_{line} = T \times P_{node} \tag{16}$$

Among them,  $P_{line}$  is the branch active power flow vector.

Then, for branch k (node m-n) and node i, the k-th row i-column element of the T matrix is:

$$T_{k,i} = \frac{X_{m,i} - X_{n,i}}{x_k}$$
(17)

Among them,  $x_k$  is the reactance of branch k,  $X_{m,i}$  and  $X_{m,j}$  are the elements of the corresponding position of the node reactance matrix X, and  $T_{k,i}$  is the element of the corresponding position of the T matrix.

The locational marginal price (LMP) was calculated. When the network loss is not considered, the LMP consists of two parts: the system energy price and transmission congestion price:

$$\rho = -\lambda e - T^{1} \mu \tag{18}$$

Among them,  $\rho$  is the LMP vector for all the nodes, e is the unit vector,  $\mu$  is the Lagrange multiplier vectors corresponding to all the branch power constraints, and  $\lambda$  is the Lagrange multiplier corresponding to the power balance constraint.

The LMP of the transmission and distribution contact node can be calculated as follows:

$$\lambda_B = \rho_i \tag{19}$$

Among them,  $\lambda_B$  is the LMP of the distribution network node and *i* is the transmission and distribution contact node.

The following is the calculation for the change ratio of the LMP to the energy price:

$$x_{\lambda} = \frac{\lambda_B - \lambda}{\lambda} \tag{20}$$

Among them,  $\lambda$  is the energy price and  $\alpha_{\lambda}$  is the proportion of the change of the LMP relative to the energy price, that is, the synergistic compensation coefficient.

We then adjusted the compensation price of the flexible load according to  $\alpha_{\lambda}$  and amended the transmission and distribution coordinates to adjust for the compensation price. Combined with the above dynamic step compensation method, the dynamic cooperative compensation method was used to solve the congestion.

The line blocking coefficient *W* was defined to measure the blocking degree of the line using the following formula:

$$W = \frac{|P_l(t)| - P_{l\max}}{P_{l\max}}$$
(21)

Among them,  $P_{lmax}$  is the capacity of the *l*th line,  $P_l(t)$  is the power flow of the *l*th line. In the formula, if W > 0, it means that the line is blocked. The larger the value is, the more serious the blocking is. If  $W \le 0$ , it means that the line is not blocked.

#### 3.2. Active Distribution Network Layer Model

The distribution network layer takes the node electricity price issued by the transmission network layer as the known condition and takes the minimum dispatching cost as the goal. Considering the optimal cost of purchasing electricity from the transmission network, controllable unit power generation, flexible load compensation, and energy storage charging and discharging costs [22,23], in order to increase the consumption of clean energy, the penalty cost of abandoning wind and light is added to the objective function, resulting in the acquisition of the active distribution network scheduling scheme. The mathematical model is as follows:

Objective function:

$$\min C_{ADN} = C_B + C_{MT} + C_{FL} + C_{ES} + C_{NE}$$
(22)

$$C_B = \sum_{t=1}^{T} \left( \lambda_t P_B^t \right) \tag{23}$$

$$C_{MT} = \sum_{t=1}^{T} \left[ a (P_{MT}^{t})^{2} + b P_{MT}^{t} + c \right]$$
(24)

$$C_{ES} = \sum_{t=1}^{T} \left( \lambda_{ES} \left| P_{ES}^t \right| \right)$$
(25)

$$C_{NE} = \sum_{t=1}^{T} \left( \lambda_{WT} \Delta P_{WT}^{t} + \lambda_{PV} \Delta P_{PV}^{t} \right)$$
(26)

Among them,  $C_B$  is the cost of purchasing electricity from the transmission network,  $\lambda_t$  is the node price at the time of t, and  $P_B^t$  is the purchase of electricity from the distribution network to the transmission network.  $C_{MT}$  is the cost of gas turbine power generation;  $P_{MT}^t$  is the output of gas turbine in t period; a, b, and c are the quadratic term coefficient, primary term coefficient, and the constant term of the gas turbine power generation cost;  $C_{FL}$  is the compensation cost for a flexible load;  $C_{ES}$  is energy storage charge and discharge

cost;  $\lambda_{ES}$  is the charging and discharging price of energy storage;  $P_{ES}^t$  is the charging and discharging power of energy storage;  $C_{NE}$  is the cost of abandoning wind and light;  $\lambda_{WT}$  and  $\lambda_{PV}$  are the punishment prices of abandoning wind and light; and  $\Delta P_{WT}^t$  and  $\Delta P_{PV}^t$  are the amounts of abandoning wind and light.

The compensation cost for flexible loads includes the compensation cost for interruptible loads, shiftable loads, and transferable loads, which are calculated as follows:

$$C_{FL} = C_{IL} + C_{SL} + C_{TL} \tag{27}$$

$$C_{IL} = \sum_{t=1}^{T} (1 + \alpha_{\lambda}^{t}) \lambda_{IL}^{t} P_{IL}^{t}$$
(28)

$$C_{SL} = \sum_{i=1}^{N_{SL}} (1 + \alpha_{\lambda}^{t_0^i}) \lambda_{SL,i} P_{SL,i}$$
(29)

$$C_{TL} = \sum_{t=1}^{T} \left( 1 + \alpha_{\lambda}^{t} \right) \lambda_{TL} \left| P_{TL}^{t} \right|$$
(30)

Among them,  $C_{IL}$ ,  $C_{SL}$ , and  $C_{TL}$  are the compensation costs for an interruptible, shiftable, and transferable load, respectively.  $P_{IL}^t$  is the outage power at time t,  $P_{TL}^t$  is the transfer power at time t,  $P_{SL,i}$  is the shiftable load power of the *i*th response scheduling,  $N_{SL}$  is the number of shiftable loads,  $\lambda_{IL}^t$  is the compensation price of the unit power of an interruptible load at time t,  $\lambda_{TL}$  is the compensation price of the unit power of a transferable load, and  $\lambda_{SL,i}$  is the compensation price of the shiftable load of the *i*th response scheduling.  $\alpha_{\lambda}^t$  is the change ratio at time t,  $\alpha_{\lambda}^{t_0^i}$  is the change ratio of the shiftable load of the *i*th response scheduling at the moment  $t_0$ , and  $t_0^i$  is the original start time of electricity consumption. The constraints of the system are as follows:

The power balance constraints are calculating using the following formulas:

$$P_B^t = P_L^t - P_{MT}^t - P_{ES}^t - P_{WT}^t - P_{PV}^t$$
(31)

$$P_L^t = P_{GL}^t + P_{SL}^t + (P_{IL0}^t - P_{IL}^t) + (P_{TL0}^t - P_{TL}^t)$$
(32)

Among them,  $P_{WT}^t$  and  $P_{PV}^t$  are the amounts of wind and light consumption.  $P_L^t$  is the load of the distribution network at time *t*.  $P_{GL}^t$  is the rigid load of the distribution network at time *t*.  $P_{GL}^t$  is the rigid load of the distribution network at time *t*.  $P_{IL0}^t$  is the total transferable load at time *t*.  $P_{IL0}^t$  is the interrupt power at time *t*.  $P_{TL0}^t$  is the total transferable load at time *t*.  $P_{TL}^t$  is the transferable load at time *t*.  $P_{TL0}^t$  is the transferable load at time *t*.

The power purchase constraint can be calculated as follows:

$$|P_B^t| \le P_B^{\max} \tag{33}$$

Among them,  $P_B^{\text{max}}$  is the maximum amount of purchased electricity for the distribution network, mainly determined using the upper limit of the tie-line power transmission and level of power supply.

The constraints of the schedulable resources are as follows:

The gas turbine constraints include the upper and lower limits of the output and ramp rate constraints, which are calculated using the following formulas:

$$P_{MT}^{\min} \le P_{MT}^t \le P_{MT}^{\max} \tag{34}$$

$$P_{MT}^{t-1} - DR \le P_{MT}^t \le P_{MT}^{t-1} + UR \tag{35}$$

Among them,  $P_{MT}^t$  is the output of the gas turbine at time *t*,  $P_{MT}^{max}$  and  $P_{MT}^{min}$  are the upper and lower limits of the output of the gas turbine, and *UR* and *DR* are the limits of the increase or decrease in the output of the gas turbine.

For energy storage equipment, there are SOC constraints, charge and discharge power constraints, and the same constraints of the first and last states, which are as follows:

$$SOC_{\min} \le E_t \le SOC_{\max}$$
 (36)

$$charge: E_t = E_{t-1} + P_C^t \eta_C$$

$$discharge: E_t = E_{t-1} - \frac{P_D^t}{\eta_D}$$
(37)

$$E_0 = E_t \tag{38}$$

$$P_{ES}^t = P_C^t - P_D^t \tag{39}$$

Among them,  $SOC_{max}$  and  $SOC_{min}$  are the maximum capacity and minimum capacity of the energy storage equipment, respectively.  $E_t$  is the power of the energy storage device at time t. It is required that the power is the same at the beginning and end of a scheduling cycle.  $P_C^t$  and  $P_D^t$  are the charging and discharging power for energy storage equipment.  $\eta_C$  and  $\eta_D$  are the charging and discharging efficiencies of energy storage equipment.  $P_{ES}^t$ is the charge and discharge power, where a positive value represents charge and a negative value represents discharge.

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For a flexible load, there are interruptible load constraints, shiftable load constraints, and transferable load constraints:

Interruptible load constraints include maximum and minimum outage capacity constraints, maximum outage times constraints, and outage duration constraints:

$$P_{IL\min}^t \le P_{IL}^t \le P_{IL\max}^t \tag{40}$$

Among them,  $P_{IL\min}^t$  and  $P_{IL\max}^t$  are the minimum interrupt power and the maximum interrupt capacity.  $P_{IL}^t$  is the interrupt power at time *t*.

$$k_{IL} \le k_{IL_{\max}} \tag{41}$$

Among them,  $k_{IL_{max}}$  is the maximum number of interruptions.

$$_{IL} \le t_{IL_{\max}} \tag{42}$$

Among them,  $t_{IL_{max}}$  is the maximum interruption duration. The shiftable load constraint includes the longest shift time constraint:

t

$$t_{SL} \le t_{SL_{\max}} \tag{43}$$

Among them,  $t_{SL_{max}}$  is the longest translation time for electric vehicles.

The transferable load includes the upper and lower limits of transferable power constraints and the total transfer power constraints:

$$P_{TL\min}^t \le P_{TL}^t \le P_{TL\max}^t \tag{44}$$

Among them,  $P_{TLmin}^t$  and  $P_{TLmax}^t$  are the minimum transferable power and the maximum interrupt capacity.  $P_{TL}^t$  is the transferable power at time *t*.

The sum of the transfer power is 0, which is calculated as follows:

$$\sum_{t=1}^{T} P_{TL}^{t} = 0 \tag{45}$$

The new energy constraint is the constraint of wind and light consumption:

$$0 \le P_{WTpre}^{t} - P_{WT}^{t} \le \Delta P_{WTmax}^{t}$$

$$0 \le P_{PVvre}^{t} - P_{PV}^{t} \le \Delta P_{PVmax}^{t}$$

$$(46)$$

Among them,  $P_{WTpre}^t$  and  $P_{PVpre}^t$  are the predicted outputs of wind and light at time t.  $P_{WT}^t$  and  $P_{PV}^t$  are the amounts of wind and light consumption at time t.  $\Delta P_{WTmax}^t$  and  $\Delta P_{PVmax}^t$  are the maximum amounts of abandoned wind and light.

The reserve constraint is calculated using the following formula:

$$R_{down}^{t} = (P_{WTup}^{t} - P_{WTpre}^{t}) + (P_{PVup}^{t} - P_{PVpre}^{t})$$

$$R_{up}^{t} = (P_{WTpre}^{t} - P_{WTdown}^{t}) + (P_{PVpre}^{t} - P_{PVdown}^{t})$$
(47)

Among them,  $P_{WTup}^t$  and  $P_{PVup}^t$  are the upper limits of the wind and solar output at time *t*.  $P_{WTdown}^t$  and  $P_{PVdown}^t$  are the lower limits of wind and solar output at time *t*.  $R_{up}^t$  and  $R_{down}^t$  are the positive and negative reserves of the gas turbine to the wind at time *t*.

#### 3.3. Solution Method and Process

Mathematically, bi-level optimization is a non-convex and nonlinear problem, which is solved using intelligent algorithms. The transmission network layer is the optimal power flow problem, which is solved using the primal-dual interior point method. The distribution network layer is solved using the particle swarm optimization algorithm.

The particle swarm optimization (PSO) algorithm searches for the global optimal and individual optimal particles by continuously updating the velocity and position of the particles to find the optimal solution of the problem.

Suppose that the position and velocity of the *i*-th particle in the *d*-dimensional search domain are:

$$X_{i} = (x_{i,1}, x_{i,2}, \cdots, x_{i,d})$$

$$V_{i} = (v_{i,1}, v_{i,2}, \cdots, v_{i,d})$$
(48)

The speed and position updates are:

$$v_{i,j}(t+1) = \omega v_{i,j}(t) + c_1 r_1 [p_{i,j} - x_{i,j}(t)] + c_2 r_2 [p_{g,j} - x_{i,j}(t)]$$
(49)

$$x_{i,j}(t+1) = x_{i,j}(t) + v_{i,j}(t+1)$$
(50)

Among them,  $\omega$  is the inertia weight,  $c_1$  and  $c_2$  are the learning factors, and  $r_1$  and  $r_2$  are 0~1 random numbers.  $v_{i,j}(t)$  is the speed after *t*th iterations.  $x_{i,j}(t)$  is the position after *t*th iterations.  $p_{i,j}$  is the individual optimal value and  $p_{g,j}$  is the global optimal value.

The algorithm flow of the particle swarm is as follows:

- 1. We set the basic parameters of the algorithm, initialized the particle position and velocity, and modified the particle position according to the constraint conditions. We then calculated the particle fitness, after which each particle was evaluated and the individual optimal position and the global optimal position were obtained;
- 2. We updated the position and velocity of the particles, modified the particle position according to the constraint conditions, after which the particle fitness function value was calculated and the historical individual optimal position and global optimal position of the particle were updated;
- 3. Lastly, we determined whether the number of iterations reached the maximum number of iterations. If the maximum number of iterations is reached, the result is output, otherwise, it returns 2.

The decision variable of the optimal scheduling of the active distribution network is the active power of each power source at each moment. By changing the position and speed of the particles, the output is adjusted until the optimal solution is reached. The transmission and distribution network exchanges information between the two layers through the node price and the power purchase of the distribution network. The convergence condition is that the iterative results meet the accuracy requirements.

### 4. Example Analysis

## 4.1. Simulation Scenario Setting

Based on the modified IEEE-39 experimental system, the effectiveness of the proposed strategy was verified using a simulation. The system consisted of 39 nodes and 46 branches. The modified IEEE-39 experimental system was obtained by adding the active distribution network to node 20 of the standard IEEE-39 experimental system, as shown in Figure 4. The numbers represent the number of nodes and the letter "G" indicates the generator. In the transmission network, the upper limit of the transmission capacity of line 9 and line 37 was 1100 MW. The upper limit of the transmission capacity of line 22 was 1250 MW and the upper limit of the transmission capacity of the other transmission lines was 1010 MW. The upper limit of the transmission and distribution connection line was 800 MW. The active distribution network included schedulable resources, such as gas turbines, energy storage, wind power, photovoltaics, and flexible loads.



Figure 4. Retrofit of the IEEE-39 experimental system.

### 4.2. Comparative Analysis of the Distribution Network before and after Participation

In order to verify the effectiveness of the proposed strategy, the following scenarios were set:

Scene 1: the transmission network was blocked, the congestion was solved only via the transmission-side generator scheduling, and the distribution-side maintained the original scheduling scheme;

Scene 2: when the transmission network was blocked, the generator set, the active distribution network participated in congestion scheduling to solve the congestion, and the distribution network adopted the dynamic cooperative compensation method.

The original scheduling scheme only considered the economy. When the power flow security check was carried out, it was found that the branch was blocked, and the blocking line, blocking period, and blocking coefficient are shown in Figure 5. According to the safety check, line 22 (power flow from node 19 to node 16) was blocked, and the blocking situation was more serious in the 8th and 9th periods. Only in the 8, 9, 10, 11 and 18 periods, line congestion occurred; there was no line congestion in the other periods. The darker the color, the more serious the line congestion. The line congestion in the 8th and 9th periods is severe, the line congestion in the 10th and 11th periods is mild and the line congestion in the 18th period is moderate.



Figure 5. Line congestion under the original scheduling scheme.

The LMP, energy price, and change ratio of the contact nodes during the blocking period are shown in Figure 6. When no congestion occurred, the LMP of each node remained the same. When line 22 was blocked, the LMP of the head node 19 was reduced. Because the line between nodes 19, 20, 33 and 34 was not blocked, the node price was consistent, so the LMP of the contact node 20 also reduced. Additionally, the reduction ratio was related to the degree of line congestion.



Figure 6. LMPs of the contact node during the blocking period.

The cost comparison in each scene is shown in Table 1. The cost of solving congestion in scene 2 was lower, which was 29.51% lower than that in scene 1. Moreover, the cost of the distribution network in scene 2 was 16.98% lower. It can be seen that the transmission and distribution coordination method can effectively solve the congestion problem and reduce the congestion cost.

Table 1. Cost comparison under different scenes.

Scene	Congestion Cost (Ten Thousand Yuan)	Transmission Network Cost (Ten Thousand Yuan)	Distribution Network Cost (Ten Thousand Yuan)
Original Scheme	-	4985.93	404.26
Scene 1	1.95	4987.88	-
Scene 2	1.37	4986.08	335.63

The comparison of the bilateral adjustment of transmission and distribution in each scene is shown in Table 2. Scene 2 guides the change in the distribution network load through the node price, aiming at the lowest cost so that the transmission network power generation adjustment is larger than that of scene 1 but with a lower congestion cost.

Scene	Power Generation Adjustment on the Transmission Side (MW)	Purchase Power Adjustment on the Distribution Side (MW)
Scene 1	1000.25	-
Scene 2	1627.49	1004.37

The branch power flow of line 22 when blocking, the branch power flow after only adjusting the transmission side to resolve the blocking, and the branch power flow after the combination of transmission and distribution to resolve the blocking are compared, which is shown in Figure 7. From the diagram, it can be seen that the adjusted branch power of line 22 was lower than the maximum transmission capacity of the line, and the blocking situation disappeared.



Figure 7. The branch power comparison diagram of line 22.

When the distribution network participated in transmission congestion management, the power comparison diagrams of the gas turbine, energy storage, interruptible load, shiftable load, transferable load, wind power, and photovoltaic before and after adjustment were obtained, as shown in Figures 8–14. Due to the congestion, the LMP of the contact node changed. With the lowest cost as the goal, the power of each flexible resource was adjusted.



Figure 8. The power comparison diagram of the gas turbine.



Figure 9. The power comparison diagram of energy storage.



Figure 10. The power comparison diagram of the interruptible load.

Load Capacity/MW



Figure 11. The power comparison diagram of the shiftable load.







Figure 13. The power comparison diagram of wind.



Figure 14. The power comparison diagram of photovoltaic.

The power comparison diagram before and after the adjustment of the transmission and distribution connection line is shown in Figure 15. The positive number represents that the distribution network purchases electricity from the transmission network. The adjustment of the power of each flexible resource renders the power curve different before and after the adjustment of the transmission and distribution connection line.





### 4.3. Flexible Load Satisfaction and Compensation Price Analysis

Considering the difference in the load demand, the dynamic compensation price was obtained by dynamically dividing the satisfaction ladder according to the load satisfaction characteristics.

For the interruptible load, the relationship between the interruption power and the compensation price when the number of dynamic steps in the third and seventh periods was three and six, respectively, is shown in Figure 16, where (a) is the dynamic step of the third period, which is three, (b) is the dynamic step of the seventh period, which is three, (c) is the dynamic step of the third period, which is six, and (d) is the dynamic step of the seventh period, which is six.



**Figure 16.** The relationship between the interruption power and the compensation price. (**a**) The dynamic step of the 3rd period, which is 3; (**b**) The dynamic step of the 7th period, which is 3; (**c**) the dynamic step of the 3rd period, which is 6; and (**d**) the dynamic step of the 7<sup>th</sup> period, which is 6.

Since a single interruptible load has a small capacity and is scattered and the satisfaction is affected by temperature, the satisfaction probability density function at different temperatures can simply integrate the scattered load to obtain the interruptible power in different satisfaction ranges. Due to the low temperature in the third period, it is more likely to have low satisfaction after the interruption of the heat pump load, so the interruption range of the lower compensation price is smaller.

For the shiftable load and transferable load, the relationship between the satisfaction and the compensation price when the number of dynamic steps is three and nine, respectively, is shown in Figure 17, where (a) is the dynamic step, which is three and (b) is the dynamic step, which is nine. The average satisfaction interval was divided. The higher the satisfaction, the lower the compensation price and the smaller the span of the compensation price when the number of dynamic steps is larger.



**Figure 17.** The relationship between satisfaction and compensation price. (**a**) The dynamic step is 3; (**b**) The dynamic step is 9.

The relationship between the translation duration of the translatable load and the satisfaction is shown in Figure 18a. The maximum translation time was set to 8 h, and the satisfaction could be maintained at a high level. The power consumption time was 1, 2, 3 or 4 h. The relationship between the transfer power of the transferable load and the satisfaction is shown in Figure 18b. The relationship between the transfer duration duration and satisfaction and the relationship between transfer power and satisfaction were simplified to a linear relationship.



**Figure 18.** The relationship between translation duration or transfer power and satisfaction. (**a**) Translation duration and satisfaction. (**b**) Transfer power and satisfaction.

The dynamic ladder can render the dynamic compensation price under a certain degree of satisfaction, stimulate the enthusiasm of the demand response, meet the load satisfaction, and render the scheduling more flexible.

Using the dynamic collaborative compensation method, the dynamic step compensation price was obtained. Compared with the fixed-step compensation price, the cost pairs of transmission and distribution coordination to solve the congestion are shown in Table 3. Among them, the fixed step compensation price was only related to the interruption power, the translation time, and the transfer power. The steps were evenly distributed, and the interruption power range, the translation time range, and the transfer power range were the same under the same compensation price.

Table 3. The cost comparison under different compensation methods.

Scene	Congestion Cost	Transmission Network Cost	Distribution Network Cost
	(Ten Thousand Yuan)	(Ten Thousand Yuan)	(Ten Thousand Yuan)
Dynamic Step	1.37	4986.08	335.63
Fixed Step	4.48	4990.41	337.24

When the transmission and distribution coordination method was used to solve the congestion, the number of dynamic steps of interruptible load, shiftable load, and transferable load was optimized to be three, nine, and three, respectively. When the fixed step compensation method was adopted, the number of fixed steps was six. According to the data in the table, it can be seen that the dynamic collaborative compensation method can significantly reduce the congestion cost, and it is more flexible. It can reduce the cost of the transmission network and distribution network while ensuring load satisfaction.

### 4.4. Comparative Analysis under Different Degrees of Congestion

By changing the transmission capacity limit of transmission line 22, the line was blocked to varying degrees.

Scenario 1: The transmission capacity of line 22 was reduced to 90% of the original;

Scenario 2: The transmission capacity of line 22 was increased to 110% of the original. The line blocking coefficient of the corresponding period is shown in Figure 19 and

the node price is shown in Figure 20.



Line Blocking Coefficient

Figure 19. Line congestion after changing the line transmission capacity.

According to the data in the Figure 19, it can be seen that changing the transmission capacity of the line directly affects the blocking of the line. After reducing the transmission capacity, the blocking coefficient of the line becomes larger, and the blocking is more serious. After increasing the transmission capacity, the blocking coefficient of the line decreases or even becomes negative, and the degree of blocking decreases or no blocking occurs. After increasing the transmission capacity, there was no line blocking in periods 10, 11, and 18.



The value greater than the red dashed line indicates that the congestion is severe. The value in the range of 0 to the red dashed line indicates that the blocking degree is not too severe. The value less than 0 indicates that the line is not blocked.



Furthermore, according to the data in the Figure 20, the degree of congestion directly affects the node electricity price. As the head node of the blocked line, the node electricity price of the contact node decreases, encouraging the load at the contact node to increase, reducing the line congestion. Moreover, with an increase in the severity of congestion, the proportion of the node electricity price decreases.

The cost comparison under different congestion levels is shown in Table 4, and whether the distribution network is involved in congestion management is considered. According to the data comparison, it can be seen that when the transmission capacity of the line is reduced, the congestion is serious, and the congestion cost is higher. When the distribution network participates in congestion management, the congestion cost is lower, which was 29.51%, 25.93%, and 16.38% lower than that of the transmission side adjustment. Due to the increase in the transmission capacity, line 22 only had slight congestion in the 8th and 9th periods, so the congestion cost was low and the cost of the two solutions was not significantly different. Comparing the total cost, it can be seen that when the line transmission capacity is larger, the total cost of only adjusting the transmission side is lower, and the total cost is lower when the distribution network participates in congestion management.

Table 4. The cost comparison under different degrees of congestion.

Scenario	Whether the Distribution Network is Involved	Congestion Cost (Ten Thousand Yuan)	Transmission Network Cost (Ten Thousand Yuan)	Distribution Network Cost (Ten Thousand Yuan)	Total Cost of Transmission and Distribution Network (Ten Thousand Yuan)
Transmission Capacity is Not Changed.	Yes	1.37	4986.08	335.63	5321.71
	No	1.95	4987.88	404.26	5392.14
Scenario 1	Yes	4.50	4990.44	324.56	5315.00
	No	6.08	4992.01	404.26	5396.27
Scenario 2	Yes	0.057	4985.99	337.34	5323.33
	No	0.068	4986.00	404.26	5390.26

## 5. Conclusions

With the access of a large number of flexible schedulable resources in active distribution networks, in order to solve the problem of day-ahead transmission congestion, this paper proposes a bi-level optimal congestion scheduling strategy based on flexible load dynamic compensation prices, which realizes the maximum utilization of transmission and distribution resources. Using the modified IEEE-39 experimental system for simulation verification, the following conclusions are drawn:

- Considering the satisfaction characteristics of flexible loads in a distribution network layer model, the dynamic collaborative compensation method was adopted to fully mobilize the enthusiasm of the demand response and effectively improve the flexibility of transmission network scheduling;
- The transmission network layer model was based on the node price method in the congestion management mechanism. The electricity price signal was used to guide the generation and consumption of electricity so that the distribution network could respond to transmission congestion mitigation and effectively solve the transmission congestion problem;
- Through the transmission and distribution coordination method, the flexible resources in the distribution network were encouraged to participate in transmission congestion management and the transmission congestion cost was effectively reduced.

In order to reduce the difficulty of this study, the uncertainty of the load and flexibility resources was not considered. In future research, scenario-based stochastic planning [24] can be added to the model to study the impact of uncertainty.

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