A Congestion Mitigation Model of Transmission Network Considering the Participation of Distribution Companies in Power Market

Puliang Du, Zhong Chen*, Ziqi Zhang, Qi Zhao

***Abstract*—Transmission congestion management in the power market requires coordination of controllable resources in the transmission network. This paper focuses on the massive number of distributed power sources and responsive loads in power distribution companies (PDCs), and a bi-level optimal dispatch model with distribution companies as the main body participating in transmission congestion in the power market is proposed. In the transmission network model, the load of the PDC and the traditional generator set are dispatched to alleviate transmission network congestion under the condition of minimum cost. In the PDC model, the unit adjustment cost and user satisfaction of the distribution company are taken as the objectives to schedule the resource. Considering the competition and compensation relationship of objectives in the model, a new multi-objective solution method is proposed to realize the effective scheduling of resources in the PDC. Moreover, the analytical target cascading (ATC) method is employed in the bi-level model to decouple the transmission network and PDC model. Finally, to illustrate the feasibility of the proposed model, simulation studies are conducted on the T6D2 system. The stability and effectiveness of the model are verified by multiple comparisons.**

***Index Terms*—congestion management, power market, bi-level optimal dispatching, ATC method.**

I. INTRODUCTION

In recent years, with the global energy change, the penetration rate of renewable energy, mainly wind power, in the power grid is gradually increasing [1]. This makes the grid congestion phenomenon caused by the volatility of renewable energy in the operation process more and more prominent. With the deepening of China's power market reform, the medium and long-term market trading power continues to increase, and the proportion of renewable energy cross-regional trading is also increasing [2], transmission grid congestion has become an urgent problem to be solved.

According to the transaction mechanism of the power market, when congestion occurs in the transmission lines, it is necessary to adjust the transaction plan in the market in a very short time to mitigate the congestion and ensure the safe operation of the power grid [4]. At present, the congestion mitigation of transmission networks mainly depends on dispatching the output of generating units or directly cutting off the load, which makes the congestion management cost higher [5-7]. With a large number of distributed power generation and controllable load access to the distribution network, the flexibility of the distribution network has been significantly improved. At the same time, the research on active distribution networks (ADNs) has greatly improved the controllability of the distribution network [8]. As the direct management department of the distribution network, the power distribution companies (PDC) will also have higher flexibility in the dispatching process. Therefore, it is possible for PDCs to participate in transmission congestion mitigation in the power market.

At present, a series of studies on transmission and distribution network coordination have been carried out. Sun et al. [9] proposed a master-slave-splitting method to solve the problem of power flow calculation in the process of coordinated dispatching of transmission and distribution networks. Li et al. [10] introduced an economic dispatch model of transmission and distribution coordination. The heterogeneous decomposition algorithm is used to solve the model, and the effectiveness of the proposed method is demonstrated. The coordinated dispatching of transmission and distribution networks is studied in [11], which solves the problems of transmission network planning, load recovery, and reactive power optimization, respectively. From the above research, it can be concluded that the current research on transmission and distribution coordination does not consider the power market trading mechanism. In addition, the research on transmission and distribution coordination to solve the transmission network congestion problem is still generally uncharted territory.

In the spot power market, how to determine the optimal market quotation of PDCs and obtain the most economic congestion management scheme for the transmission network is the key to the transmission network congestion mitigation with the participation of PDCs. In the actual operation process, the transmission network obtains the bidding information through the spot power market and formulates the scheme with the minimum congestion management cost. The PDCs respond to the market incentive by coordinating their internal resources. The transmission network and distribution network operate independently, but the optimization results influence each other, which is a typical bi-level programming model [12]. At present, the bi-level programming model also has a certain application in the power market. For example, Jenabi

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et al. [14] discussed the planning of grid-connected power generation and transmission and distribution expansion, based on which, a bi-level game model for the coordination of transmission planning under market environment is proposed. Sheikhahmadi et al. [15] investigated the coordination among transmission, distribution, and distribution energy resource (DER) aggregators that interact in a local market model and proposed a bi-level optimization approach to derive the optimal result. In Sharifi et al. [16] and Foroughi et al. [17], the bi-level optimization model is used to optimize the market bidding of retailers and the optimal bidding of multiple virtual power plants. Considering the advantages of the bi-level programming model in solving multi-level decision-making groups in the power market, a bi-level optimization-based transmission network congestion mitigation model with the participation of PDCs is constructed in the current paper. The bi-level model is usually solved by means of distributed algorithms, mainly involving the following three categories [18]: (i) the Lagrangian relaxation-based methods, such as the analytical target cascading (ATC) [19] and alternating direction method of multipliers (ADMM) [20]; (ii) the Karush-Kuhn-Tucker (KKT) conditions based methods, such as heterogeneous decomposition (HGD) [22]; (iii) the benders decomposition (BD) method. Among these methods, the ATC method is widely used because it does not require the model to be strictly convex. Based on this consideration, the ATC method is adopted in this paper to solve the proposed congestion mitigation model.

To sum up, the main contributions of this study can be summarized as:

1) Based on the transaction mechanism of the power market, a bi-level model of transmission congestion mitigation considering the participation of PDC is proposed.

2) Considering that the model of the PDC layer is an optimization problem involving multiple objectives, a competitive-compensatory goal programming approach is proposed to effectively solve the objectives.

3) The distribution network power flow calculation is linearized to maximize the solution speed of the model to meet the time demand of the power market. Besides, the ATC method is used to introduce the coupling variables into the bi-level model in the form of a penalty function to realize the decoupling of the bi-level model.

The remainder of the paper is organized as follows. Section 2 introduces the congestion dispatching management framework of transmission and distribution cooperative power grid in the power market. Section 3 provides a detailed description and the corresponding mathematical model of the framework. The solution of the model is introduced in Section 4. The proposed model is validated with the help of a case study in Section 5. Section 6 concludes this paper.

II. THE CONGESTION DISPATCHING MANAGEMENT FRAMEWORK OF TRANSMISSION AND DISTRIBUTION COOPERATIVE POWER GRID IN THE POWER MARKET

In China, the power spot market currently mainly carries out day-ahead, intra-day, real-time power trading and auxiliary service trading such as standby and frequency regulation, and has been running on a pilot basis in several cities such as Shandong, Shanxi, and Guangdong. The development of the power spot market has enriched the mode and means of power trading, which has laid a good foundation for the distribution network to participate in market interaction.

With the increasing penetration of distributed generation and flexible load in the distribution network, the flexibility of the distribution network has been greatly improved, making the PDC has a certain response-ability. In the actual operation process, the PDC can monitor the data by supervisory control and data acquisition (SCADA) system, dispatch the internal resources through the distribution management system (DMS), and finally formulate the corresponding bidding scheme to participate in the spot power market.

As shown in Fig. 1, when the overload occurs in the transmission line, the transmission network monitoring device will collect data and transmit it to the power transmission network dispatching center. At this point, each conventional power plant and distribution company provides bidding information to the power spot market. The transmission grid dispatch center technically confirms the market parameters and operating parameters of the market participants and determines the adjustment plan for each market participant to minimize transmission grid blockage mitigation costs. Finally, the adjusted power is issued to each market participant. After receiving the adjusted power from the transmission grid, the power distribution company calculates the adjusted power of responsive users and distributed generating units as well as the unit power dispatch tariff of the distribution company with the goal of highest customer satisfaction and lowest unit power dispatch cost, and finally reports the obtained results to the power spot market. At this time, the electricity spot market updates the bidding information, and the transmission grid dispatch center determines the adjustment plan for each market participant again based on the updated bidding information. This is repeated until the adjustment plan issued by the dispatching center is consistent with that obtained by each distribution company after optimization. At this point, each distribution company participating in transmission grid blockage mitigation completes bidding and obtains authorization in the spot market, and the transmission grid sends adjustment plans to each participant to solve the transmission grid blockage problem.

III. FORMULATION OF THE BI-LEVEL CONGESTION MITIGATION MODEL

Based on the congestion dispatching management framework of the transmission and distribution cooperative power grid in the power market described in section II, a bi-level optimization model integrating the transmission network and the PDC is established.

A. Transmission network model

According to the bidding and adjustable capacity parameters of each entity participating in the spot power market, the transmission network model determines the adjustment scheme with the minimum congestion management cost as the objective. The mathematical model is as follows:

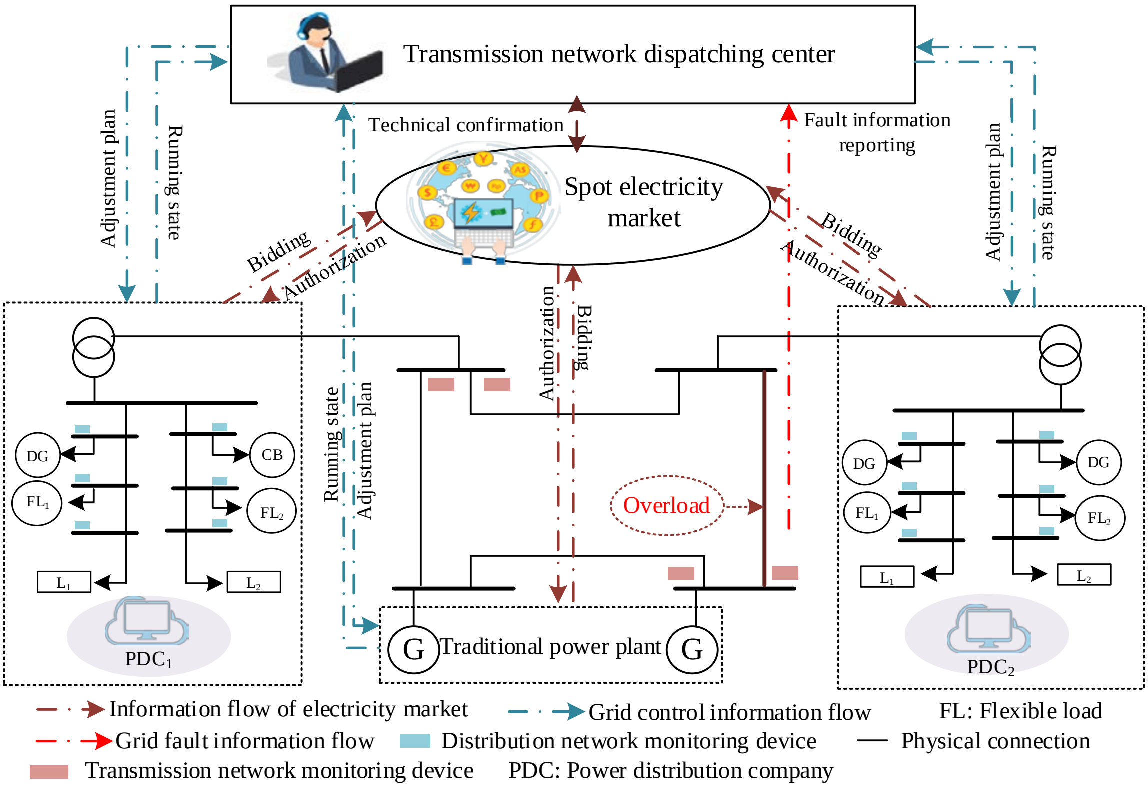

Fig. 1. The transmission network congestion management framework considering PDC participation.

$$\min f_1 = F_G + F_{PDC} \tag{1}$$

where F_G and F_{PDC} are the cost of generating units and the response cost of PDCs respectively. The specific expressions of F_G and F_{PDC} are as follows:

$$F_G = \sum_{i=1}^{m}\left(a_{G,i}^{+}\Delta P_{G,i}^{+} + a_{G,i}^{-}\Delta P_{G,i}^{-}\right) \tag{2}$$

$$F_{PDC} = \sum_{n=1}^{Td} b_n \Delta P_{PDC_n} \tag{3}$$

where m is the number of generating units participating in the spot power market in the transmission network, $a_{G,i}^{+}$ and $a_{G,i}^{-}$ represent the unit power up and down dispatching costs of generating unit i, $\Delta P_{G,i}^{+}$ and $\Delta P_{G,i}^{-}$ represent the increased and decreased power of generator i, Td is the number of PDC, b_n represents the unit power dispatching price of PDC_n participating in the spot power market, and ΔP_{PDC_n} represents the power dispatched by PDC_n. Moreover, considering that it is difficult for PDC to increase the user's load, only the load reduction capacity of PDC is employed to participate in the spot power market dispatching.

Constraints of the transmission network layer model:

① Power flow constraints

$$\mathbf{P} = \mathbf{B\theta} \tag{4a}$$

$$\mathbf{P} = \mathbf{P}_{MT} - \mathbf{P}_{load} - \mathbf{P}_{PDC} \tag{4b}$$

$$P_{ij} = \frac{\theta_i - \theta_j}{x_{ij}} \tag{4c}$$

where $\mathbf{P}_{MT}$, $\mathbf{P}_{load}$, $\mathbf{P}_{PDC}$, $\mathbf{P}$, and $\boldsymbol{\theta}$ represent the generator active power vectors of all nodes except balance node, active power vector of load, active power vector of PDC, active power vector injected by node, and phase angle vector of node voltage, respectively. P_{ij} is the active power flowing through branch *i*-*j*, and x_{ij} is the reactance of branch *i*-*j*.

② Generator constraints

$$w_{d,i} \le \left(\Delta P_{G,i}^{+} + \Delta P_{G,i}^{-}\right) \le w_{u,i} \tag{5a}$$

$$P_{G,i}^{\min} \le P_{T,G,i} + \left(\Delta P_{G,i}^{+} + \Delta P_{G,i}^{-}\right) \le P_{G,i}^{\max} \tag{5b}$$

where $w_{d,i}$ and $w_{u,i}$ are the downhill and uphill climbing capacities of generator set i, respectively. $P_{G,i}$ is the current output of generator i in the transmission network, $P_{G,i}^{\min}$ and $P_{G,i}^{\max}$ are the minimum and maximum generating power of generator set i, respectively.

③ The scheduling margin constraint of PDC

$$\Delta P_{PDC_j} \le \Delta P_{PDC_j}^{\max} \tag{6}$$

where $\Delta P_{PDC_j}^{\max}$ is the maximum active power that PDC_j can dispatch.

④ Security constraint

$$\left|P_l\right| \le \sigma_l P_l^{\max} \tag{7}$$

where σ_l is the safety margin coefficient of the branch l, and $P_l^{\max}$ is the maximum power allowed to flow through the branch l, and P_l is the current power flowing through the branch l.

⑤ Power scheduling constraint

$$\Delta P_{l-need} = \sum_{i=1}^{N_T} G_{l-i}\left(\Delta P_{T,G,i}^{+} + \Delta P_{T,G,i}^{-}\right) + \sum_{j=1}^{N_T} G_{l-j}\Delta P_{PDC_j} \tag{8}$$

where ΔP_{l-need} is the power that branch l needs to reduce to solve the overload, G_{l-i} is the sensitivity factor of generator i

to branch *l*, and G_{l-j} is the sensitivity factor of PDC_j to branch *l*.

B. The optimization model of PDC

In the response process, PDCs need to fully ensure customer satisfaction and reduce the extra expenses in the operation of the distribution network. Therefore, this paper takes the regulation cost and user response satisfaction of distributed generation units in the distribution network of PDC as the goal to build the optimal scheduling model. The following takes PDC_n as an example to introduce the model.

Objective function：

$$\begin{cases} f_{2\text{-}1}^{n} = \min \sum_{i=1}^{T_n} s_i^n \Delta P_i^n \\ f_{2\text{-}2}^{n} = \max S^n \end{cases} \tag{9}$$

where T_n is the number of distributed generating units in the PDC_n, s_i^n represents the unit output cost of generator *i* in the PDC_n, ΔP_i^n represents the increased output of generator *i* in the PDC_n, and S^n is the comprehensive satisfaction of users in PDC_n (as shown in Eq. (10)).

$$S^n = \alpha C_1^n + \beta C_2^n \tag{10}$$

$$C_1^n = \frac{1}{\phi_n} \sum_{i=1}^{\phi_n} \frac{\Delta P_{user,i}^{PDC_n}}{\Delta P_{user,i}^{PDC_n,\max}} \tag{11}$$

$$C_2^n = \frac{bb_n}{2v} \tag{12}$$

$$\Delta P_{PDC_n}^{Dis} = \sum_{i=1}^{\phi_n} \Delta P_{user,i}^{PDC_n} + \sum_{i=1}^{T_n} \Delta P_i^n \tag{13}$$

where C_1^n represents the user's satisfaction degree of power consumption comfort, C_2^n represents the user's satisfaction degree of power consumption cost. α and β are the weights of C_1^n and C_2^n, respectively. v is the power purchase price at time *t*, ϕ_n is the compensation price of the number of users in PDC_n, bb_n is the compensation price of user response load, κ_n is the number of controllable distributed generators in PDC_n. $\Delta P_{user,i}^{PDC_n,\max}$ and $\Delta P_{user,i}^{PDC_n}$ are the maximum responsive load and the actual responsive load of user *i*, respectively. $\Delta P_{PDC_n}^{Dis}$ is the active power quantity responded by PDC_n after the optimization of the PDC model.

The constraints of PDC_n：

① Power flow constraints

$$\sum_{i\in\Omega(j)} \left[P_{ij}^{PDC_n} - r_{ij}^{PDC_n} \frac{\left(P_{ij}^{PDC_n}\right)^2 + \left(Q_{ij}^{PDC_n}\right)^2}{\left(U_i^{PDC_n}\right)^2} \right] = \sum_{k\in\mho(j)} P_{jk}^{PDC_n} + P_j^{PDC_n} \tag{14a}$$

$$\sum_{i\in\Omega(j)} \left[Q_{ij}^{PDC_n} - x_{ij}^{PDC_n} \frac{\left(P_{ij}^{PDC_n}\right)^2 + \left(Q_{ij}^{PDC_n}\right)^2}{\left(U_i^{PDC_n}\right)^2} \right] = \sum_{k\in\mho(\mathrm{j})} Q_{jk}^{PDC_n} + Q_j^{PDC_n} \tag{14b}$$

$$P_j^{PDC_n} = P_{MT_j}^{PDC_n} - P_{user_j}^{PDC_n} \tag{14c}$$

$$Q_j^{PDC_n} = Q_{MT_j}^{PDC_n} - Q_{user_j}^{PDC_n} \tag{14d}$$

$$\begin{aligned} \left(U_j^{PDC_n}\right)^2 &= \left(U_i^{PDC_n}\right)^2 - 2\left(r_{ij}^{PDC_n} P_{ij}^{PDC_n} + x_{ij}^{PDC_n} Q_{ij}^{PDC_n}\right) \\ &+ \left[\left(r_{ij}^{PDC_n}\right)^2 + \left(x_{ij}^{PDC_n}\right)^2\right] \frac{\left(P_{ij}^{PDC_n}\right)^2 + \left(Q_{ij}^{PDC_n}\right)^2}{\left(U_i^{PDC_n}\right)^2} \end{aligned} \tag{14e}$$

where $\Omega(j)$ represent the set of first nodes of the branch with *j* as the node in the distribution network *n*, $\mho(j)$ represent the set of end nodes of the branch in the distribution network *n* with *j* as the first end node. $P_j^{PDC_n}$ and $Q_j^{PDC_n}$ represent the active and reactive power injected by node *j*, $P_{MT_j}^{PDC_n}$ and $Q_{MT_j}^{PDC_n}$ represent the power output and reactive power output of the distributed generator in node *j*, $P_{user_j}^{PDC_n}$ and $Q_{user_j}^{PDC_n}$ are the active and reactive power of the user at node j respectively, $r_{ij}^{PDC_n}$ and $x_{ij}^{PDC_n}$ are the resistance and reactance of the branch *i-j* respectively, and $U_j^{PDC_n}$ is the voltage amplitude of node *j*.

Taking into account the speed of model solving, this paper uses the second-order cone optimization theory proposed in [8] to linearize the power flow calculation of the distribution network. First, $\left(I_{ij}^{PDC_j}\right)^2$ is defined according to Eq. (15):

$$\left(I_{ij}^{PDC_j}\right)^2 = \frac{\left(P_{ij}^{PDC_n}\right)^2 + \left(Q_{ij}^{PDC_n}\right)^2}{\left(U_i^{PDC_n}\right)^2} \tag{15}$$

Let $\tilde{I}_{ij}^{PDC_n} = \left(I_{ij}^{PDC_n}\right)^2$ and $\tilde{U}_j^{PDC_n} = \left(U_j^{PDC_n}\right)^2$, the original expressions in Eqs. (14a)-(14e) can be transformed into Eqs.(16a)-(16e), as shown below:

$$\sum_{i\in\Omega(j)} \left[P_{ij}^{PDC_n} - r_{ij}^{PDC_n} \tilde{I}_{ij}^{PDC_n} \right] = \sum_{k\in\mho(j)} P_{jk}^{PDC_n} + P_j^{PDC_n} \tag{16a}$$

$$\sum_{i\in\Omega(j)} \left[Q_{ij}^{PDC_n} - x_{ij}^{PDC_n} \tilde{I}_{ij}^{PDC_n} \right] = \sum_{k\in\mho(\mathrm{j})} Q_{jk}^{PDC_n} + Q_j^{PDC_n} \tag{16b}$$

$$P_j^{PDC_n} = P_{MT_j}^{PDC_n} - P_{user_j}^{PDC_n} \tag{16c}$$

$$Q_j^{PDC_n} = Q_{MT_j}^{PDC_n} - Q_{user_j}^{PDC_n} \tag{16d}$$

$$\begin{aligned} \tilde{U}_j^{PDC_n} &= \tilde{U}_i^{PDC_n} - 2\left(r_{ij}^{PDC_n} P_{ij}^{PDC_n} + x_{ij}^{PDC_n} Q_{ij}^{PDC_n}\right) \\ &+ \left[\left(r_{ij}^{PDC_n}\right)^2 + \left(x_{ij}^{PDC_n}\right)^2\right] \tilde{I}_{ij}^{PDC_n} \end{aligned} \tag{16e}$$

Then, we relax Eq. (15) and get the following result:

$$\left(I_{ij}^{PDC_n}\right)^2 \geq \frac{\left(P_{ij}^{PDC_n}\right)^2 + \left(Q_{ij}^{PDC_n}\right)^2}{\left(U_i^{PDC_n}\right)^2} \tag{17}$$

The inequality constraint in Eq. (17) is further transformed into the standard second-order cone by equivalent deformation, as shown in Eq. (18).

$$\left\| \begin{matrix} 2P_{ij}^{PDC_n} \\ 2Q_{ij}^{PDC_n} \\ \tilde{I}_{ij}^{PDC_n} - \tilde{U}_{ij}^{PDC_n} \end{matrix} \right\| \leq \tilde{I}_{ij}^{PDC_n} + \tilde{U}_{ij}^{PDC_n} \tag{18}$$

② Security constraints of distribution network

$$U_{\min,i} \leq \tilde{U}_{i,t}^{PDC_n} \leq U_{\max,i} \tag{19a}$$

$$\sqrt{\left(P_i^{PDC_n}\right)^2 + \left(Q_i^{PDC_n}\right)^2} \leq S_{i,\max}^{PDC_n} \tag{19b}$$

$$\sqrt{\left(P_{ij}^{PDC_n}\right)^2 + \left(Q_{ij}^{PDC_n}\right)^2} \leq S_{ij,\max}^{PDC_n} \tag{19c}$$

where $U_{\max,i}$ and $U_{\min,i}$ are the maximum and minimum voltages allowed by node *i*, and $S_{i,\max}^{PDC_n}$ and $S_{ij,\max}^{PDC_n}$ are the maximum apparent power allowed by node *i* and branch *i-j* respectively.

③ The constraints of user satisfaction

$$C_1^{\min} \le C_1 \le 1 \tag{20a}$$

$$C_2^{\min} \le C_2 \le 1 \tag{20b}$$

④ The constraint of user compensation tariff

$$v \le bb_n \le 2v \tag{21}$$

⑤ The constraint of generator in PDC_n

$$P_{MT_j,\min}^{PDC_n} \le P_{MT_j}^{PDC_n} \le P_{MT_j,\max}^{PDC_n} \tag{22}$$

where $P_{MT_j,\max}^{PDC_n}$ and $P_{MT_j,\min}^{PDC_n}$ are the maximum and minimum output of the generator in PDC_n, respectively.

⑥ The constraint of the response margin in PDC_n

$$\Delta P_{PDC_n}^{\max} = \sum_{j=1}^{\kappa_n}\left(P_{MT_j,\max}^{PDC_n} - P_{MT_j}^{PDC_n}\right) + \sum_{i=1}^{\phi_n}\left(\Delta P_{user,i}^{PDC_n,\max}\right) \tag{23}$$

where $P_{MT_j,\max}^{PDC_n}$ is the maximum output of MT_j, $P_{MT_j}^{PDC_n}$ is the current output of generator *j*.

Through the optimization calculation of the PDC model, the final bid for participating in the congestion management of the transmission network can be obtained, as shown in Eq. (24).

$$b_n = \frac{bb_n \sum_{i=1}^{\phi_n} \Delta P_{user,i}^{PDC_n} + \sum_{i=1}^{\kappa_n} s_i^n \Delta P_i^n}{\Delta P_{PDC_n}^{Dis}} \tag{24}$$

After the PDC model is optimized, the b_n and $\Delta P_{PDC_n}^{Dis}$ are fed back to the transmission network, and the bidding information in the spot power market is updated at the same time. The dispatching center of the transmission network executes the optimal dispatching model of the transmission network again until the final agreement is reached between the dispatching center of the transmission network and the participants of the spot power market. The solution of the proposed bi-level model will be explained in detail in the following section.

IV. SOLUTION METHOD

For the bi-level optimization model introduced in this paper, there are two problems to be considered: (1) the PDC model is a multi-objective model, which is difficult to solve directly; (2) the transmission network and the distribution network are operated separately, but their dispatching results usually affect each other, so it is extremely challenging to deal with the bi-level model with a global optimization method. Aiming at the first point, we propose a multi-objective solution method, namely the competitive-compensatory goal programming approach. In addition, considering that ATC method is a popular tool to handle the multi-level and multi-body coordination and optimization problems, it has the advantages of unlimited series, easy parameter selection, and overcomes the phenomenon that the traditional dual decomposition algorithm based on lagrange relaxation is prone to repeated oscillation in the iteration. The convergence of the ATC method has been rigorously proven in Tosserams et al. [23]. Therefore, the ATC method is utilized in this paper to solve the proposed bi-level model, i.e., the second point mentioned above.

A. *Multi-objective solution method in PDC model*

Since the PDC model takes scheduling cost and satisfaction of the users as the goal, it is a multi-objective problem. For the multi-objective problem, the commonly used solution method is to convert it into a single objective optimization problem. In response to this, we propose a competitive-compensatory goal programming approach to solve the PDC model.

First, let $G_1^n = \sum_{i=1}^{T_n} C_i^n \Delta P_i^n$, $G_2^n = S^n$, $G_3^n = \sum_{i=1}^{N_n} \sum_{j\in\Omega(i)} \tilde{I}_{ij}^{PDC_n}$, and $G_4^n = \left|\Delta P_{PDC_n}^{Tran} - \Delta P_{PDC_n}^{Dis}\right|$. The PDC model can be expressed as the following model, denoted as model 1.

$$\text{(Model 1)} \quad \begin{cases} Min\ Y_1^n = \left\{ G_1^n \mid Min(G_3^n + G_4^n)\right\} \\ Max\ Y_2^n = \left\{ G_2^n \mid Min(G_3^n + G_4^n)\right\} \end{cases}$$
$$s.t. \quad \text{Eq. (10)-(24)}$$

Then, we construct the respective membership function μ_1 and μ_2 for the above two objectives:

$$\mu_1 = \frac{U_1 - Y_1^n}{U_1 - L_1} \tag{25}$$

$$\mu_2 = \frac{Y_2^n - L_2}{U_2 - L_2} \tag{26}$$

where L_1 and U_2 respectively represent the optimal values of objectives Y_1^n and Y_2^n that are independently optimized with the same constraints as the above model, i.e.,

$$\begin{cases} L_1 = Min\ Y_1^n = \left\{ G_1^n \mid Min(G_3^n + G_4^n)\right\} \\ s.t. \quad \text{Eq. (10)-(24)} \end{cases} \tag{27}$$

$$\begin{cases} U_2 = Max\ Y_2^n = \left\{ G_2^n \mid Min(G_3^n + G_4^n)\right\} \\ s.t. \quad \text{Eq. (10)-(24)} \end{cases} \tag{28}$$

Additionally, we set U_1 and L_2 as the tolerance limits of the goal Y_1^n and Y_2^n respectively, which can be stated as:

$$U_1 = Y_{1,Cmax}^n, \quad L_2 = Y_{2,Cmin}^n$$

where C_{max}/C_{min} denotes the corresponding maximum/ minimum value of the objective in the presence of the other objectives with respect to the given constraints. More specifically, $Y_{1,Cmax}^n$ is the obtained value of objective Y_1^n at the optimal point of Y_2^n. In a similar way, we can determine the tolerance for the objective Y_2^n.

Then, based on the characterization of the membership functions μ_1 and μ_2, we can obtain the equivalent form of model 1 by using the competitive-compensatory goal programming approach, which utilizes a hybrid technique consisting of a competitive "Min" operator and a compensatory "Simple arithmetic average" operator. The corresponding model is stated as:

$$Max: \eta^n + (1-\theta)\frac{1}{2}\sum \eta_i^n \tag{29}$$

$$\begin{aligned}
&\text{Subject to: } \mu_1^n \geq \eta^n + \eta_1^n, \mu_2^n \geq \eta^n + \eta_2^n, \\
&\mu_1 = \frac{U_1 - Y_1^n}{U_1 - L_1}, \mu_2 = \frac{Y_2^n - L_2}{U_2 - L_2}, \\
&Y_1^n = \left\{ \sum_{i=1}^{T_n} C_i^n \Delta P_i^n \mid Min(G_3^n + G_4^n) \right\}, \\
&Y_2^n = \left\{ S^n \mid Min(G_3^n + G_4^n) \right\}, \\
&G_3^n = \sum_{i=1}^{N_n} \sum_{j \in \Omega(i)} \tilde{I}_{ij}^{PDC_n}, \\
&G_4^n = \left| \Delta P_{PDC_n}^{Tran} - \Delta P_{PDC_n}^{Dis} \right|, \\
&\mu_1^n \leq 1, \ \ \mu_2^n \leq 1, \\
&\eta^n, \eta_1^n, \eta_2^n, \theta \in [0,1], \\
&\text{Eq. (10)-(28)}
\end{aligned} \tag{30}$$

We can obtain different optimization results based on the competitive-compensatory relationship of two objective functions by changing the value of the compensation parameter θ. It can be seen that when θ=1, the two objectives are in a competitive relationship, and the PDC model gets the common maximum of the two objectives. When the value of the parameter θ is less than 1, the compensation relationship between the two goals begins to enter the optimization process. The higher goal achievement level tends to compensate the satisfaction of the lower goal achievement level and obtain the optimal result. Therefore, the dispatchers can reasonably set the compensation parameters according to the different decision-making requirements of the distribution network to ensure the interests of PDCs.

B. Objective function reconstruction

In the upper and lower levels of the bi-level congestion mitigation model (i.e., the transmission network model and the PDC model), there are coupling variables in each level, which prevents the upper and lower levels from being solved independently. In view of this, under the framework of the ATC algorithm, the coupling variables are relaxed to the objective function in the form of a penalty function to realize the decoupling of the model. Therefore, the upper and lower objective functions need to be reconstructed.

Reconstruction of the objective function in transmission network model:

$$\begin{aligned}
&\min f_1^{(k)} = F_G^{(k)} + F_{PDC}^{(k)} \\
&+\sum_{n=1}^{Td} \left\{ \begin{aligned} &\omega_{1,k} \left(\Delta P_{PDC_n}^{Tran,(k)} - \Delta \overline{P}_{PDC_n}^{Dis,(k)} \right) \\ &+ \left[\omega_{2,k} \left(\Delta P_{PDC_n}^{Tran,(k)} - \Delta \overline{P}_{PDC_n}^{Dis,(k)} \right) \right]^2 \end{aligned} \right\}
\end{aligned} \tag{31}$$

Reconstruction of the objective function in the PDC model:

$$\begin{aligned}
&\min f_2^{n,(k)} = -\eta^{n,(k)} - (1-\gamma)\frac{1}{2}\sum \eta_i^{n,(k)} + \lambda_1 \sum_{i=1}^{N_n} \sum_{j \in \Omega(i)} \tilde{I}_{ij}^{PDC_n} + \\
&\omega_{1,k} \left(\Delta \overline{P}_{PDC_n}^{Tran,(k)} - \Delta P_{PDC_n}^{Dis,(k)} \right) + \left[\omega_{2,k} \left(\Delta \overline{P}_{PDC_n}^{Tran,(k)} - \Delta P_{PDC_n}^{Dis,(k)} \right) \right]^2
\end{aligned} \tag{32}$$

where $\omega_{1,k}$ and $\omega_{2,k}$ are the algorithm multipliers of the *k*th iteration. $\Delta \overline{P}_{PDC_n}^{Tran,(k)}$ and $\Delta \overline{P}_{PDC_n}^{Dis,(k)}$ are the coupling variables in the transmission network model and PDC model, respectively. $\Omega(i)$ is the collection of branches with *i* as the head node in the distribution network. To ensure the validity of the solution, λ_1 is set as a large constant to make the power flow calculation within the effective range. In the solution process, the multiplier of the algorithm is constantly updated and iterated, so that the coupling variables are close to each other in the calculation process and eventually keep consistent.

C. Solving flow

The transmission network congestion mitigation flow chart based on the ATC algorithm is shown in Fig. 2.

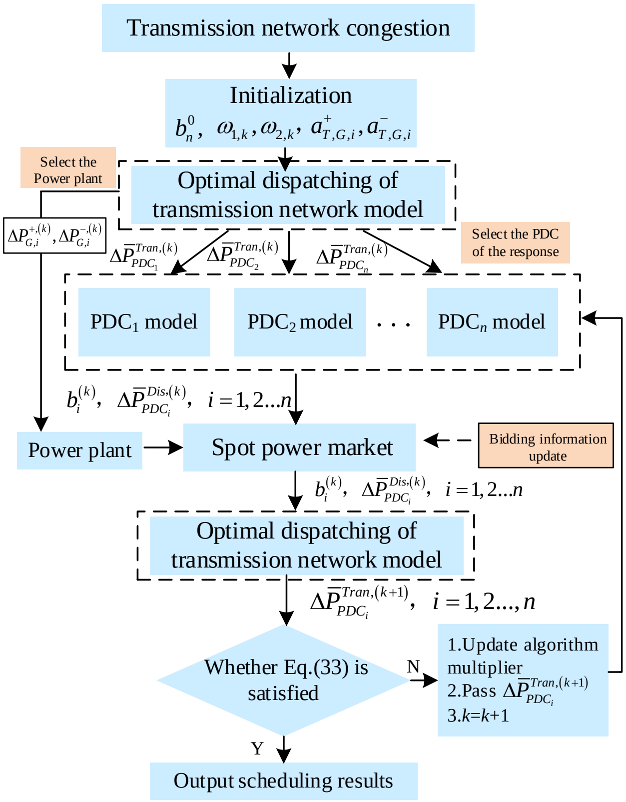

Fig. 2. Transmission network congestion mitigation flow chart based on ATC algorithm.

The specific steps are as follows:

Step1: When congestion occurs, it is assumed that the PDC_n dispatches electricity price as b_n^0 at this time and initialize $\omega_{1,k}$, $\omega_{2,k}$, and *k*. Then, the power plants and PDCs that can participate in congestion dispatching can be selected by the means of the transmission network model, and specific dispatching results can be obtained. The results $\Delta \overline{P}_{PDC_n}^{Tran,(k)}$, $\Delta P_{G,i}^{+,(k)}$, and $\Delta P_{G,i}^{-,(k)}$ are distributed to each power plant and PDC.

Step 2: The PDC model takes Eq. (32) as the objective to conduct the optimal dispatching, so as to obtain the optimal price $b_i^{(k)}$ and response load $\Delta P_{PDC_n}^{Dis,(k)}$. Let $\Delta \overline{P}_{PDC_n}^{Dis,(k)} = \Delta P_{PDC_n}^{Dis,(k)}$, and then transmit the $b_i^{(k)}$ and $\Delta \overline{P}_{PDC_n}^{Dis,(k)}$ to the power market for bidding.

Step 3: The spot power market update the quotation information of each PDC and power plant.

Step 4: According to the data of the spot power market, the transmission network dispatching center implements the transmission network model with Eq. (32) as the target and obtains the load adjustment amount $\Delta P_{PDC_n}^{Tran,(k+1)}$ of each PDC.

Step 5: Execute Eq. (33) to determine whether the coupling variables are consistent. If not, update the algorithm multiplier according to Eq. (34), and let $\Delta \overline{P}_{PDC_n}^{Tran,(k+1)} = \Delta P_{PDC_n}^{Tran,(k+1)}$, send the load adjustment amount $\Delta \overline{P}_{PDC_n}^{Tran,(k+1)}$ of each PDC to the PDC model, and return to Step 2 for iteration. If Eq. (33) is satisfied, At this time, the transmission grid dispatch center confirms the dispatch results and outputs the final results. At the same time, the distribution network completes bidding and authorizes in the power spot market, finally realizing the relief of transmission network blockage.

$$\sum_{i=1}^{Td} \left| \Delta P_{PDC_i}^{Tran,(k+1)} - \Delta \overline{P}_{PDC_i}^{Dis,(k)} \right| \le \zeta \tag{33}$$

$$\begin{cases} \omega_{1,k+1} = \omega_{1,k} + 2\left(\omega_{2,k}\right)^2 \sum_{i=1}^{Td} \left(\Delta P_{PDC_i}^{Tran,(k)} - \Delta P_{PDC_i}^{Dis,(k)} \right) \\ \omega_{2,k+1} = \gamma \omega_{2,k} \end{cases} \tag{34}$$

where ζ is the convergence coefficient, γ is a constant, and the initial values of $\omega_{1,k}$ and $\omega_{2,k}$ are generally small constants.

V. CASE ANALYSIS

In this section, the T6D2 system is adopted to validate the proposed model. The congestion scenario of transmission network is constructed, and the influence of the electricity sales company on congestion management is discussed. In addition, the effectiveness of the proposed method is further proved. The optimization model in the case study is solved by programming in MATLAB, calling the CPLEX software.

A. *Case introduction*

The T6D2 system is shown in Fig.3, which includes a 6-bus transmission network and two PDCs. All the parameters of the system are the same as in Kargarian and Fu [24]. To verify the effectiveness of the proposed method, we assume that the allowable power of each transmission line is 45MW, the maximum output of the distributed generation unit of each PDC is 3MW, and the maximum response power of each flexible load node is 1MW. The unit output cost of distributed generation unit is 600 yuan/MW. Loads of the 3, 4, and 5 nodes of the transmission network are 50MW, 80MW, and 40MW respectively. The adjustment cost of each generation unit in the transmission network is shown in Table I.

TABLE I
THE ADJUSTMENT COST OF OUTPUT FOR GENERATING UNIT

	G1	G2	G3
Increase	330yuan/MW	320yuan/MW	300yuan/MW
Reduce	280yuan/MW	280yuan/MW	280yuan/MW

Assuming that in actual operation, the power generation costs of the three power plants are 400 yuan/MW, 420 yuan/MW, and 400 yuan/MW, respectively. In the case of only considering the economics of the transmission network, the detailed information of each element in the transmission network is shown in Fig. 4.

It can be seen from the results in Fig. 4 that the power of line 2 exceeds the allowable power when only the economy is taken into consideration, and thus the transmission network needs to carry out congestion dispatching. In response to this scenario, this paper conducts the following analysis based on the spot power market transaction mechanism.

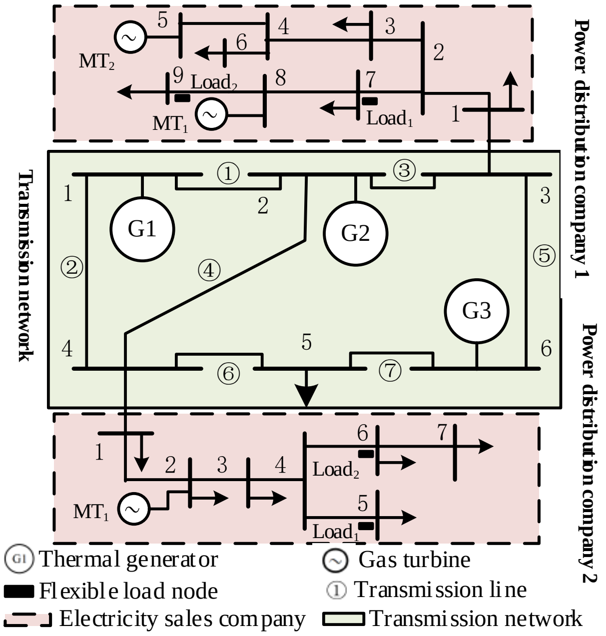

Fig. 3. The revised structure diagram of transmission network and distribution network.

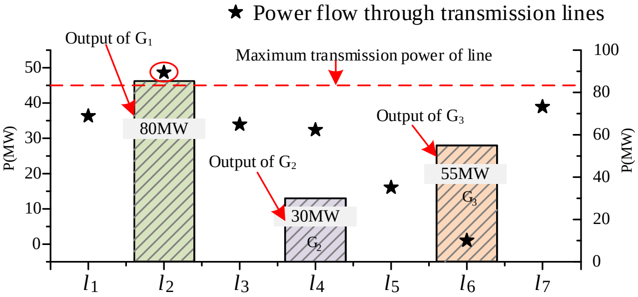

Fig. 4. The output of units and the power flow of the lines in the transmission network.

B. *Comparative analysis of electricity sales companies before and after participation*

To prove the effectiveness of the proposed method, the following two scenarios are established：

Scenario 1: In the spot electricity market, the congestion of transmission network only depends on dispatching power plants.

Scenario 2: In the spot electricity market, the congestion of transmission network is alleviated by dispatching power plants and electricity sales companies. Let $\gamma = 1.5$, $\omega_{1,k} = 0.5$, $\omega_{1,k} = 0.5$, $\zeta = 0.01$, $\alpha = 2/3$, $\beta = 1/3$, and θ=0.3. The electricity purchase price for users is 0.5 yuan/kWh.

Table II provides the adjustment of each unit and the total cost in the process of mitigating transformation network congestion with respect to Scenario 1. Fig. 5 shows the output and line congestion of each unit in Scenario 1 when the PDC does not participate in the power spot market. It can be found that the transmission line congestion has been alleviated by dispatching power plants G1 and G2. Moreover, we find that G3 is not involved in the entire congestion dispatching process. This is because power plant G3 is less sensitive to the overload line, so it has not been authorized by the power spot market.

TABLE II
DISPATCHING RESULTS OF ELECTRICITY SALES COMPANIES NOT PARTICIPATING IN SPOT ELECTRICITY MARKET

	Increase	Reduce	Total cost
G1	——	11.535 MW	6921.2yuan
G2	11.535 MW	——	

In Scenario 2, the proposed method is utilized to alleviate the congestion of the transmission network. After 15 iterations, the final congestion mitigation cost is 6868.7 yuan. Fig. 6 shows the situation of the transmission network after the transmission network congestion is relieved. The response of each PDC is illustrated in Table III. From the results of Fig. 6 and Table III, it can be found that with the participation of PDC in the spot electricity market, the power adjustment of power plants is significantly reduced. At this time, the load response subsidy cost of the PSC is 788.64 yuan/MWh, and customer satisfaction is 68.07%. By comparing the results of Scenario 1 and Scenario 2, the method proposed in this paper reduces the congestion mitigation cost of the transmission network model and realizes a win-win of the transmission network and PDC.

In addition, although both PDC_1 and PDC_2 participate in the power spot market, not all companies can obtain the power market adjustment authorization. The authorization depends on the sensitivity of the company's adjusted output to the overload line. Since PDC_1 is not very sensitive to the overload line, it is not authorized during the adjustment process.

TABLE III
RESPONSE OF PDCS

	MT$_1$	MT$_2$	Load$_1$	Load$_2$
PDC$_1$	1.49	——	0.446	0.445
PDC$_2$	0	0	0	0

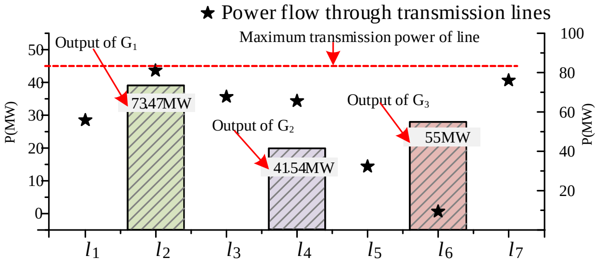

Fig. 5. The output of units and the power flow of the lines in transmission network under line constraints.

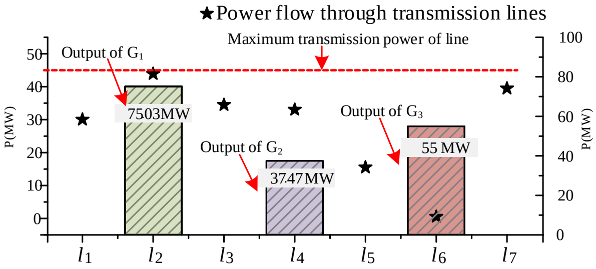

Fig. 6. Results of congestion dispatch involving PDC.

C. Influence of different compensation parameters on the results

To analyze the influence of the compensation parameter in multi-objective solution method of solving the PDC model on the results, we take different values of θ, including θ=1, θ=0.8, and θ=0. The optimal results with respect to Scenario 2 under different values of θ are shown in Table IV.

TABLE IV
COMPARISON OF RESULTS UNDER DIFFERENT COMPENSATION PARAMETERS

		Increase	Reduce	Compensation price	Total cost
θ=1	G$_1$	——	9.901MW	1499.3 yuan/MW	6892.3 yuan
	G$_2$	8.593MW	——		
	PDC$_2$	——	——		
	MT$_1$	1.804MW			
	Load$_1$		0.096MW		
	Load$_2$		0.096MW		
θ=0.8	G$_1$	——	9.911MW	1189.5 Yuan/MW	6875.3 yuan
	G$_2$	8.493MW	——		
	PDC$_2$	——	——		
	MT$_1$	1.654MW			
	Load$_1$		0.206MW		
	Load$_2$		0.206MW		
θ=0	G$_1$	——	10.0MW	783.5 Yuan/MW	6706.3 yuan
	G$_2$	7.32MW	——		
	PDC$_2$	——	——		
	MT$_1$	1.414MW			
	Load$_1$		0.456MW		
	Load$_2$		0.456MW		

It can be seen from the results that the total cost decreases with the decrease of compensation parameter, and the compensation relationship is formed between the two objective functions of customer satisfaction and the adjustment cost of the distribution network. This makes the bidding price of power distribution companies in the power market continue to decrease, thus reducing the overall congestion mitigation cost of the transmission network. On the contrary, if the compensation parameter is relatively large, the competitive relationship between the objective functions of the PDC dominates. To ensure the minimum adjustment cost and highest customer satisfaction, distribution companies will continue to increase the compensation price of users, which makes the bidding price in the power market higher, and eventually leads to an increase of congestion mitigation cost in the transmission network.

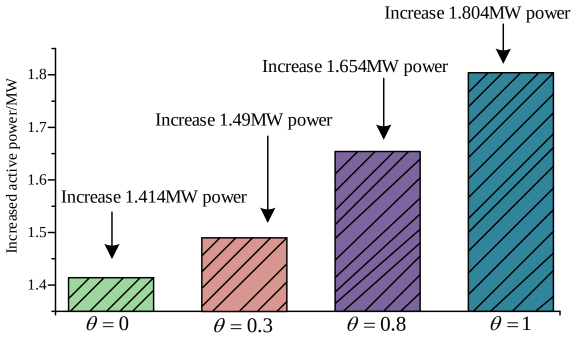

Fig. 7. The output of MT$_1$ under different θ.

On the other hand, from the results in Fig. 7, we can find that as θ decreases, the output of the distributed generating units in the PDC decreases gradually, which will allow the distributed generating units to have a higher regulation margin and can better cope with the uncertainty on the load side.

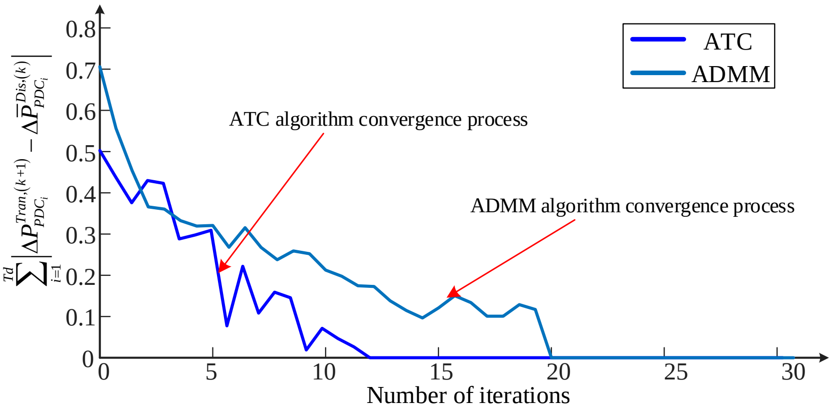

Fig. 8. Comparison of convergence between ATC algorithm and ADMM algorithm

However, no matter how the compensation parameter is adjusted, the congestion mitigation cost in Scenario 2 is less than that in Scenario 1. Therefore, it is feasible and beneficial for PDCs to participate in transmission congestion mitigation in the future. In addition, during the dispatching process, the decision-makers of PDCs need to consider the operation state of the distribution network comprehensively and determine the reasonable compensation parameter to participate in the congestion dispatching of the transmission network.

D. *Proof of algorithm validity*

To prove the effectiveness of the ATC method in solving the congestion mitigation model presented in this paper, the centralized method and ADMM method are selected as the comparison method to solve the same model in Scenario 2. The comparison result is shown in Table V.

It can be seen from Table V that there is no significant difference between the results obtained by the three methods. Although the centralized method results in a bit lower total congestion mitigation cost, it is difficult to adapt to the physical relationship between transmission and distribution networks, and therefore can not be used in the actual situation. The ATC and ADMM methods can adapt to the physical connection relationship of the transmission and distribution networks to alleviate transmission network congestion. In addition, as can be seen from Fig. 8, compared with the ADMM algorithm, the ATC algorithm performs better in the solution process, and the solution of the model can be realized after 12 iterations. According to the final results in Table V, the final result obtained by the ATC algorithm is also superior to that based on the ADMM algorithm.

TABLE V
COMPARISON OF CENTRALIZED AND DISTRIBUTED METHODS

		Increase	Reduce	Compensation price	Total cost
ATC	G_1	——	9.97MW	788.64 yuan/MW	6866 yuan
	G_2	7.48MW	——		
	ESC_1	——	——		
	DG_1	1.49MW			
	$Load_1$		0.446MW		
	$Load_2$		0.445MW		
ADMM	G_1	——	9.89MW	795.3 yuan/MW	6899.3 yuan
	G_2	7.53MW	——		
	ESC_1	——	——		
	DG_1	1.44MW			
	$Load_1$		0.455MW		
	$Load_2$		0.485MW		
Centralized	G_1	——	10.0MW	778.5 yuan/MW	6832.3 yuan
	G_2	7.38MW	——		
	ESC_1	——	——		
	DG_1	1.43MW			
	$Load_1$		0.445MW		
	$Load_2$		0.445MW		

VI. CONCLUSION

With the continuous improvement of the electricity market mechanism and the strengthening of the flexibility of power distribution, it has become possible for electricity sales companies to participate in electricity market bidding as the main body. In the spot power market, in order to realize the congestion mitigation of the transmission network in the spot market, this paper proposes a transmission and distribution collaborative congestion mitigation model considering the participation of PDCs. The ATC method is used to solve the proposed model to maximize the utilization of the whole network resources. Through the simulation and analysis, the following conclusions are drawn:

1) In the process of transmission network congestion mitigation, the participation of distribution companies will effectively reduce the cost of alleviating transmission network congestion and realize the efficient utilization of transmission and distribution grid resources.

2) In the optimal dispatching model of the distribution network, the decision-makers of PDC can dispatch the resources in the PDC by setting the reasonable compensation coefficient according to the actual situation of the distribution company. The proposed PDC model can not only alleviate the congestion of the transmission network, but also ensure the interests of distribution companies.

3) The ATC method can effectively solve the coupling relationship between the transmission network layer and the PDC layer, and realize the effective solution of the bi-level congestion mitigation model.

In addition, in the PDC model, this paper only considers the distributed generation units and users' demands. With the continuous development of the distribution network, electric vehicles, energy storage, and renewable energy will be continuously connected in the future. Therefore, in future research, it is necessary to enrich the elements of distribution companies and pay attention to the impact of the uncertainty of renewable energy on the optimization results of the model.

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