

Virtual P2P Transaction Integrated Expansion Planning for Distribution Networks

Jiakun Dai, Yue Xiang^{ID}, *Senior Member, IEEE, Senior Member, CSEE*, and Yongtao Guo

Abstract—More electricity utilities will participate in the investment and operation of private distributed generations (DGs) while the local power company is responsible for the reinforcement of lines and DGs, as well. How to achieve the maximum benefits among various utilities, including the power company, is a task in the expansion planning of distribution networks. To solve the market-oriented planning problem, virtual peer to peer (P2P) trading is integrated and modeled in the new expansion planning of distribution networks. First, virtual market transaction optimization among prosumers is formulated. Second, the distributed regional marginal price (DLMP) is calculated by the optimal operation model, which contributed to the network usage charge (NUC) and then integrated in the expansion planning model. Case studies are performed and indicate the integrated P2P transaction strategy could improve local load consumption, while reducing the load rate of lines, as well as the electricity cost of users. Besides, the total planning cost paid by the power company could be saved via prosumers' investment and P2P transactions and the factors affecting power company's profit are also classified in multi-investor planning of distribution networks.

Index Terms—Distribution network planning, distributed generation, network usage charge, prosumers, virtual P2P transactions.

NOMENCLATURE

Pro_{P2P}	Social benefit.
$N_{\text{buyer}}, N_{\text{seller}}$	Number set of electricity buyers/sellers.
d_m	Active power demand of user m .
g_n	Generation of DGs of prosumer n .
U_m, C_n	Benefit function of the buyer m / seller n .
$D_{m,\min}, D_{m,\max}$	Lower/upper limits of active power demand of user m .
$G_{n,\min}, G_{n,\max}$	Lower/upper limits of electricity generation of generator n .
p_w	Active power of the transaction w .
W	Set of P2P transactions.
$\theta_{1,n}, \theta_{2,n}, \theta_{3,n}$	Priori nonnegative parameter only related to seller n .
$\tau_{1,m}, \tau_{2,m}$	Priori nonnegative parameters related only to buyer m .

$D_{l,\text{DLMP}}$	Regional marginal electricity price of line l .
$D_{w,n,\text{DLMP}}$	Marginal bus price of seller m /buyer n in the w transaction.
$D_{w,m,\text{DLMP}}$	
$C_{\text{PC},\text{sell}}$	Profit of power company for collecting electricity charges from users.
$C_{\text{PC},\text{buy}}$	Cost of power company to purchase electricity from main grid.
$C_{\text{DG},\text{opr}}$	Cost of DGs' generation.
$C_{\text{DG},\text{invest}}$	Cost for the power company to invest in DGs.
$C_{\text{Str},\text{invest}}$	Cost of expansion of the lines' capacity.
$P_{\text{pg},m,t}$	Active load of user m at time t .
$\sigma_{\text{sell},t}$	Unit price of electricity sold by the power company at time t .
$\lambda_{\text{buy},t}$	Unit price of electricity purchased from the main grid by the power company at time t .
$\mu_{\text{buy},n}$	Unit generation cost of DGs of the power company.
$G_{\text{dg},n,t}$	Generation of the DG n at time t .
$rate_m$	Market share of P2P transactions.
$C_{\text{dg},n}$	Unit installation cost of the DG n .
$P_{\text{dg},n}$	Capacity installed of the DG n .
α	Residual value rate of equipment.
r	Discount rate.
y	Life cycle of the equipment.
N_{line}	Number of lines needed to be expanded.
$C_{\text{line},l}$	Unit cost of the expansion of line l .
L_l	Length of line l .
$Pro_{\text{PC},\text{P2P}}$	Profit from selling electricity to users.
$C_{\text{PC},\text{buy}}$	Cost of purchasing electricity from the main grid.
$C_{\text{Str},\text{invest}}$	Cost of expansion of lines.
Pro_{NUC}	NUC.
α_{NUC}	Unit price of NUC generated by P2P transactions.
$P_{\text{buy},t,\max}$	Maximum electricity purchased by power company from main grid at time t .
π_i	Set of buses at the head end of the branch with bus i as the end bus.
φ_i	Set of edge end buses headed by bus i .
r_{ki}, x_{ki}	Resistance and reactance of branch ki .
r_{ij}, x_{ij}	Resistance and reactance of branch ij .
$I_{ki,t}, I_{ij,t}$	Currents of branch ki and branch ij at time t .
$P_{ki,t}, Q_{ki,t}$	Active power and reactive power of branch ki at time t .
$P_{ij,t}, Q_{ij,t}$	Active power and reactive power of branch ij at time t .

Manuscript received December 2, 2021; revised January 22, 2022; accepted March 1, 2022. Date of online publication October 12, 2022; date of current version January 17, 2024. This work was supported by the National Natural Science Foundation of China (52177103).

J. K. Dai, Y. Xiang (corresponding author, email: xiang@scu.edu.cn; ORCID: 0000-0001-8456-1195) and Y. T. Guo are with College of Electrical Engineering, Sichuan University, Chengdu 610065, China.

DOI: 10.17775/CSEEJPES.2021.08980

	ij at time t .
$Q_{DG,i,t}$	Reactive power exchanged between the investor i and the distribution network at time t .
$Q_{buy,t}$	Reactive power purchased from main grid at time t .
$Q_{load,i,t}$	Reactive power of the original load at time t .
$V_{i,t}, V_{j,t}$	Voltages of bus i and bus j at time t .
V_{min}, V_{max}	Upper and lower limits of bus voltage.
$I_{ij,max}$	Upper current limit of branch i .
$P_{ij,max}$	Maximum active power capacity of line ij .
$P_{dg,n,max}$	Maximum installation capacity of DG n .
$N_{DG,max}$	Total number of DGs' installation buses.
$N_{lines,max}$	Total number of lines.

I. INTRODUCTION

RELEVANT strategies/policies, such as reform of the electricity market and integration of clean energy consumption and terminal transactions under a dual carbon goal, have provided an opportunity and driving force for transformation of distribution networks [1]–[3]. The energy and power sector has begun to liberalize the electricity distribution business to social capital in an orderly manner. It has also gradually liberalized incremental distribution of investment business to qualified market subjects, making investors for distribution networks and distributed energy resource planning more diversified [4], [5], including power companies and prosumers (retailers). The distribution network planning problem is challenged by the extensive addition of investors and increased demand for local load. More flexible market mechanisms and investment strategies are needed by the transfer of regional distributed production and consumption resources. Therefore, how to effectively invest/plan a reliable, economic, flexible, and multi-investor participated distribution network is an urgent topic.

Distribution network planning has become a research hotspot in recent years. Several studies on distribution network planning with DGs were investigated in [6]–[9], aiming at the distribution network's highest income or minimum loss. A model of distribution network planning considering demand response was proposed in [10], [11]. The above research belongs to single utility planning, which only considers economy and does not consider other impacts, such as safety and risk of distribution networks due to the planning. That modeling mode could face challenge when more utilities are considered. With massive integration of DGs and deepening of electricity market reform, many stakeholders, such as power companies (retailers), are involved. Generation and consumption of DGs will no longer accept unified dispatching of the local power company. Thus, only the interests of power companies is no longer applicable for the new distribution network planning situation. In [12]–[14], DG operators were regarded as independent stakeholders to optimize operation with the distribution network and establish distribution network optimal dispatching based on multi-stakeholders. A three-tier planning model that considers the interests of distribution companies, DG operators, and users was constructed in [15]. Considering

DG transaction integration and multi-stakeholder benefits, generation/load/network/storage system planning was formulated in [16]. Game theory was applied to deal with the multi-stakeholder problem in the planning [17]. However, reference studies rarely consider the transaction between DGs and electricity users, the planning results could be influenced by different electricity transaction strategies, which also impacts the profits of DGs' operators and power companies [18]. The main body of investment in the market-oriented distribution network with DG integration is no longer just the local power company, prosumers will also join in the investment and operation.

Thus, this paper mainly focuses on a market-oriented multi-investor planning method for a distribution network with DGs. A virtual P2P transaction concept is proposed to deal with a market trading simulation in the multi-stakeholder expansion planning problem among prosumers and the local power company. The planning model is formulated by three layers: operation, planning and transaction. At the transaction level, virtual P2P transactions are performed by designed market strategies, which correlated with the allocation of private DGs invested by prosumers. While reinforcement of lines and other DGs will be integrated in the operation and planning layers by the local power company.

The contributions of the paper are as follows:

- 1) The proposed trading integrated planning model can coordinate multi-stakeholders' participation in the investment and operation of the distribution network and effectively reduce expansion costs of distribution networks.
- 2) The concept of virtual P2P transaction is proposed and organically integrated into the planning with DLMP and NUC models to reflect the trading impacts.
- 3) Incentives of the local power companies to accept prosumers' investment in the distribution network planning are classified and whether can be profitable are also investigated.

The rest of the paper is as follows. A virtual P2P transaction integrated expansion planning framework is introduced in Section II. A single and multi-investor expansion planning models of the distribution network is introduced in Section III. The simulation results and discussion of cases are given in Section IV. Conclusions are summarized in Section V.

II. PLANNING FRAMEWORK OF DISTRIBUTION NETWORK INTEGRATED WITH P2P TRANSACTION

In the increasingly free competition power market, the market is open to more investors [19]. In traditional operation and planning modes of distribution networks, the power company purchases electricity from the main grid and uniformly distributes electricity to the load. The main benefits of a power company come from the price difference between electricity sales and electricity purchase. The main costs are the initial investment cost and operation cost of distribution networks.

In the mode of virtual P2P transaction integrated expansion planning of distribution networks, the responsibility of a power company is to hold safe and stable operation of the distribution network to ensure normal operation. The DGs covers the load demand in the distribution network during the

electricity trading market. When generation capacity of the DGs is insufficient, the power company purchases electricity from the main grid to supplement it. The profit source of power companies is mainly to collect the NUC generated in P2P transactions and a small amount of electricity sales revenue. The concept of DLMP is introduced in the study to formulate electricity prices reasonably and improve the time-space granularity of electricity prices [20].

The framework of the virtual P2P transaction integrated expansion planning of distribution networks is shown in Fig. 1, which includes three layers.

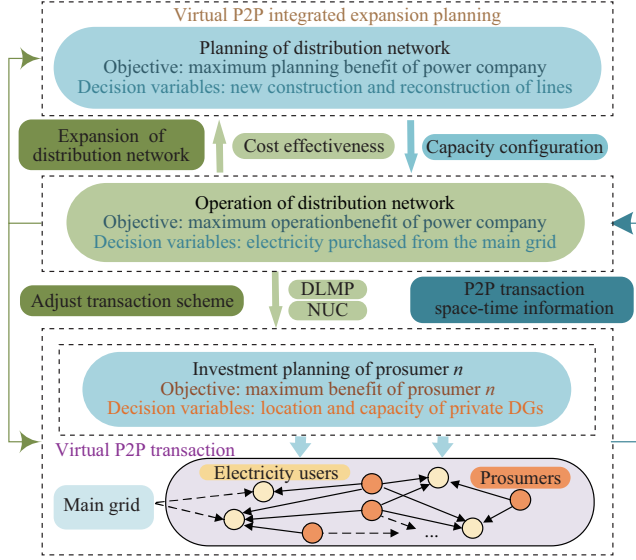


Fig. 1. Virtual P2P transaction integrated expansion planning framework.

A. Transaction (P2P trading) Layer

At virtual P2P transactions layer, the location and quantity of DGs invested by prosumers would meet their owned electricity consumption and participate in market transactions to sell electricity to users to obtain profits. On this basis, the power selling entity automatically matches according to the power purchase price and power purchase quantity of the power purchasing entity in the market, and the power purchasing entity automatically matches according to the power sale price and power sales quantity of the power selling entity.

The objective function for P2P trading is to maximize social benefits [21]:

$$\max \text{Pro}_{\text{P2P}} = \sum_{m \in N_{\text{buyer}}} U_m(d_m) - \sum_{n \in N_{\text{seller}}} C_n(g_n) \quad (1)$$

$$\text{s.t. } D_{m,\min} \leq d_m \leq D_{m,\max} \quad m \in N_{\text{buyer}} \quad (2)$$

$$G_{n,\min} \leq g_n \leq G_{n,\max} \quad n \in N_{\text{seller}} \quad (3)$$

$$d_m = \sum_{w \in W} p_w \quad m \in N_{\text{buyer}} \quad (4)$$

$$g_n = \sum_{w \in W} p_w \quad n \in N_{\text{seller}} \quad (5)$$

$$p_w \geq 0 \quad w \in W \quad (6)$$

This model balances the benefits of both parties by maximizing social benefits. Eqs. (2) and (3) are mentioned to ensure

the transaction between electricity buyers and electricity sellers complies with physical constraints. Eqs. (4), (5) and (6) are mentioned to ensure the total amount of all transactions matches electricity generation and consumption of the power system.

Sellers in the market offer their surplus energy for trading with buyers. Buyers with flexible loads participate in the market under the assumption that its flexible load is continuous, and its demand can be adjusted according to market price. Buyers' satisfaction is based on their demand for the market, which can be modeled by utility function. The benefit functions of the buyers, and the sellers [22] are:

$$C_n(g_n) = \theta_{1,n}g_n^2 + \theta_{2,n}g_n + \theta_{3,n} \quad (7)$$

$$U_m(d_m) = \begin{cases} \tau_{1,m}d_m - \tau_{2,m}d_m^2 & d_m < \omega_m/2\tau_{2,m} \\ \tau_{1,m}^2/2\tau_{2,m} & d_m \geq \omega_m/2\tau_{2,m} \end{cases} \quad (8)$$

where $\theta_{1,n}$, $\theta_{2,n}$, and $\theta_{3,n}$ are a priori nonnegative parameter only related to seller n , which reflects the amount of energy that sellers are willing to sell at different prices at a given time. These parameters are unique to each seller and depend on the power generation type of each seller. $\tau_{1,m}$, and $\tau_{2,m}$ are priori nonnegative parameters related only to buyer m and determine how a buyer responds to different prices. Since each buyer in the market acts independently, these parameters vary among buyers, at different times of the day or under climatic conditions.

The transaction scheme will be forward to the operation layer. If the corresponding optimal operation could not be achieved, the transaction scheme would be adjusted from the perspective of transaction layer. Then, the DGs configuration plan of corresponding prosumers and the transaction scheme would be adjusted according to the detailed operation status and the optimal P2P transaction models as indicated in [21].

B. Operation Layer

Optimization of the operation layer is formulated as an optimal power flow (OPF) model [23]. DLMP and NUC are calculated by using the data of operation and transaction. Given the self-optimizing transaction mode of each participant in a P2P transaction, electricity users tend to buy electricity at a lower price in the market, which may cause line congestion of the distribution network, reduce the aggregated interests of prosumers and local load consumption. This situation could be reflected by DLMP and NUC in this paper. If transactions of the P2P electricity trading cause congestion or over other safety operation limits of distribution networks, the NUC generated by this transaction would be doubled or even more. In addition, electricity price of the buses calculated according to DLMP can also encourage some P2P transactions that can improve the operation state of the whole power system. DLMP also generates additional capital flows, which can offset a decline in overall benefits due to the exclusion of DGs from transactions to some extent.

Based on the optimal operation result, DLMP could be calculated by the following equation [24]:

$$D_{l,\text{DLMP}} = A_1\lambda_{\text{receiver}(l)} + A_2\mu_{\text{output}(l)} + A_3\mu_{\text{receiver}(l)}$$

$$+ A_4 \eta_{\text{output}(l)}^+ + A_5 \eta_{\text{output}(l)}^- \quad (9)$$

where A_1 to A_5 are the price coefficient. $\lambda_{\text{receiver}(l)}$, $\mu_{\text{output}(l)}$, $\mu_{\text{receiver}(l)}$, $\eta_{\text{output}(l)}^+$ and $\eta_{\text{output}(l)}^-$ are dual variables. Then the NUC for the power company could be:

$$\text{Pro}_{\text{NUC}} = \sum_{w \in W} \sum_{m \in N_{\text{buyer}}} \sum_{n \in N_{\text{seller}}} p_{w,n,m} (D_{w,n,\text{DLMP}} - D_{w,m,\text{DLMP}}) \quad (10)$$

If there is no feasible operation solution, one way is to feed back the transaction layer to require a new transaction to be adjusted, and another way is to inform the planning layer to consider the possible reinforcement of lines.

C. Planning Layer

Prosumers are allowed to participate the planning and operation of DGs in the distribution network while paying NUC to the local power company. Reinforcement of lines will be considered by the power company to improve the transmission capacity of distribution networks to carry electricity transactions and meet improving demand. The power company collects NUC and realizes recovery of reinforcement of line capacity, operation, and maintenance costs. Capacity expansion of the corresponding lines of distribution networks would be transmitted from the planning layer to the operation level. Detailed planning models could be found in Section III. The optimal planning result can be obtained by integrating and optimizing the three layers.

III. EXPANSION PLANNING MODEL OF DISTRIBUTION NETWORK WITH SINGLE OR MULTIPLE INVESTORS

Expansion planning of distribution networks includes two modes: single investor and multi-investor.

A. Expansion Planning Objective Model of the Distribution Network by Power Company (Single Investor Mode)

In the single investor mode, expansion of lines and DGs is undertaken by the local power company. The objective function is the maximum economic profits of the power company. The benefit functions of a power company mainly include power sales revenue, cost of reinforcement of lines, and the installation expenses of DGs.

$$\text{Pro}_{\text{PC,tra}} = \text{Pro}_{\text{PC,sell}} - C_{\text{DG,opr}} - C_{\text{DG,invest}} - C_{\text{Str,invest}} \quad (11)$$

The electricity sales revenue of the power company is composed of electricity charges collected from users.

$$\text{Pro}_{\text{PC,sell}} = (\sigma_{\text{sell},t} - \lambda_{\text{buy},t}) \sum_{t \in T} \sum_{m \in N_{\text{buyer}}} P_{\text{dg},m,t} \quad (12)$$

The cost of DGs' generation is

$$\begin{aligned} C_{\text{DG,opr}} &= \mu_{\text{buy},n} \sum_{t \in T} \sum_{m \in N_{\text{buyer}}} \text{rate}_m P_{\text{pg},m,t} \\ &= \mu_{\text{buy},n} \sum_{t \in T} \sum_{n \in N_{\text{DG}}} G_{\text{dg},n,t} \end{aligned} \quad (13)$$

The cost for power company to install DGs [25] is

$$C_{\text{DG,invest}} = \sum_{n \in N_{\text{DG}}} C_{\text{dg},n} P_{\text{dg},n} \frac{r(1+r)^y - \alpha r}{(1+r)^y - 1} \quad (14)$$

The cost of reinforcement of lines is

$$C_{\text{Str,invest}} = \sum_{l \in N_{\text{line}}} C_{\text{line},l} L_l \frac{r(1+r)^y - \alpha r}{(1+r)^y - 1} \quad (15)$$

B. Expansion Planning Objective Model of the Distribution Network With P2P Transaction (Multi-investor Mode)

In a multi-investor mode, the local power company only needs to consider reinforcement of lines to maintain safe operation of distribution networks and ensure optimal P2P transactions. In this mode, the economic profits of prosumers and users need to be considered in the economic profits of the power company. The benefit function of a power company consists of electricity sales revenue, electricity purchase expenditure, NUC, and cost of reinforcement of lines:

$$\text{Pro}_{\text{PC,P2P}} = \text{Pro}_{\text{PC,sell}} + \text{Pro}_{\text{NUC}} - C_{\text{Str,invest}} \quad (16)$$

$$\text{Pro}_{\text{PC,sell}} = (\sigma_{\text{sell},t} - \lambda_{\text{buy},t}) \sum_{t \in T} \sum_{m \in N_{\text{buyer}}} (1 - \text{rate}_m) P_{\text{dg},m,t} \quad (17)$$

$$\text{Pro}_{\text{NUC}} = \sum_{w \in W} \sum_{t \in T} \sum_{m \in N_{\text{buyer}}} \sum_{n \in N_{\text{seller}}} \text{rate}_m P_{w,n,m,t} \alpha_{\text{NUC}} \quad (18)$$

The cost of electricity consumption of prosumers is included in the total price of all users. Profits of prosumers given here are obtained by prosumers investing and operating DGs. Including the cost of installation, operation and maintenance of DGs and power sales revenue:

$$\text{Pro}_{\text{DG,P2P}} = \text{Pro}_{\text{DG,sell}} - C_{\text{DG,invest}} - C_{\text{DG,opr}} \quad (19)$$

$$\text{Pro}_{\text{DG,sell}} = \sum_{t \in T} \sum_{n \in N_{\text{DG}}} \sum_{m \in N_{\text{buyer}}} \text{rate}_m P_{\text{dg},m,t} \mu_{\text{buy},t,n} G_{\text{dg},n,t} \quad (20)$$

When considering DLMP to calculate the electricity price of buses, replacing the unit price in the users' cost and the profit of prosumers from the fixed price to the DLMP is only necessary, and the NUC charged by the power company is also calculated according to (10).

C. Constraints

Either the single-investor or multi-investor modes need to meet the following constraints:

1) Power limits of electricity purchase from main grid

$$0 \leq P_{\text{buy},t} \leq P_{\text{buy},t,\text{max}} \quad (21)$$

2) Power flow balance equation [26]

$$\begin{aligned} \sum_{k \in \pi_i} (P_{ki,t} - I_{ki,t}^2 r_{ki}) &= \sum_{j \in \phi_i} P_{ij,t} - P_{\text{buy},t} \\ &\quad - P_{\text{DG},i,t} + P_{\text{load},i,t} \end{aligned} \quad (22)$$

$$\sum_{k \in \pi_i} (Q_{ki,t} - I_{ki,t}^2 x_{ki}) = \sum_{j \in \phi_i} Q_{ij,t} - Q_{\text{buy},t}$$

$$-Q_{DG,i,t} + Q_{load,i,t} \quad (23)$$

$$V_{i,t}^2 - V_{j,t}^2 = 2(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}) - I_{ij,t}^2(r_{ij}^2 + x_{ij}^2) \quad (24)$$

$$V_{i,t}^2 I_{ij,t}^2 = P_{ij,t}^2 + Q_{ij,t}^2 \quad (25)$$

3) Voltage limits

$$V_{\min} \leq V_{i,t} \leq V_{\max} \quad (26)$$

4) Lines' transmission capacity limits

$$-P_{ij,\max} \leq P_{ij,t} \leq P_{ij,\max} \quad (27)$$

5) DGs' investment capacity limits of prosumer n

$$0 \leq P_{dg,n} \leq P_{dg,n,\max} \quad (28)$$

6) Allowable number of lines reinforcement limits

$$0 \leq N_{\text{lines}} \leq N_{\text{lines},\max} \quad (29)$$

IV. CASE STUDIES

The IEEE a 33-bus system is used as the test case. The reference voltage of the distribution network is 12.66 kV, the grid structure is shown in Fig. 2. Detailed parameters of the lines are shown in Table I, while load information could be found in [27]. The electricity purchase price from the main network is 397 yuan/MW, the unit cost of lines capacity expansion is 150000 yuan/km, and the candidate incremental line capacity is 1 MW. DGs with stable output power are supposed to install at buses 1, 3, 6, 15, 19, 21, 24, and 30. The unit installation cost of DGs is 8000 yuan/MW, while the minimum installation capacity is 1 kW, and the unit operation and maintenance costs are 100 yuan/MW. These cases analyze the virtual P2P transaction integrated expansion planning of distribution networks from the perspective of the power company, prosumers, and electricity users. Since the

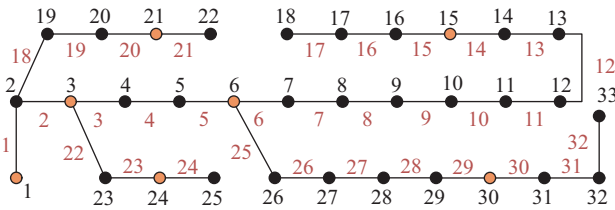


Fig. 2. Structure of IEEE 33-bus system (the orange buses are prosumers).

TABLE I
LENGTH OF 33 LINES

Number	Length (km)	Number	Length (km)	Number	Length (km)
1	1.7	12	1.2	23	0.9
2	2.7	13	2.6	24	1.6
3	2.2	14	1.2	25	2.2
4	1.9	15	1.6	26	2
5	2.22	16	2.4	27	1.1
6	1.2	17	0.7	28	1.2
7	1.2	18	1.2	29	2.2
8	2	19	2.2	30	2
9	1.1	20	2	31	1.1
10	1.1	21	1.1	32	1.2
11	1.2	22	1.2	-	-

expansion planning of either the single investor or multi-investor mode are formulated as a nonlinear integer programming problem, which could be transformed into a standard SOCP optimization format [23], which is able to be solved by *Gurobi* [28].

A. Single-investor Mode

In this case, considering the annual load growth is 25%, reinforcement of lines and DGs are considered candidate resources to be invested to meet the load demand. Based on the single-investor planning model presented in Section III, the costs and profits of the power company during five years are shown in Table II while the fifth planning result could be seen in Fig. 3.

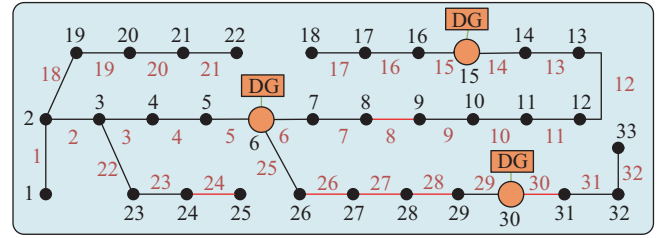


Fig. 3. Expansion planning result of single-investor mode in the fifth year (The capacity of red lines is expanded).

Given the lines' out-of-limit challenge caused by load growth, expansion of lines or DGs are considered to ensure stable operation of the distribution network by the local power company. As seen from Table II, power companies are more inclined to expand lines' capacity compared with the investment of DGs due to DGs' long cost recovery period. In early time period (year), growth of load demand is conducive to the rise in electricity sales profits, as with total profits of the power company. In the third year, existing line capacity is not enough to meet the increase of the power flow caused by load growth, thus capacity of lines needs to be expanded. From that time period, total profits of the power company begin to decline. In the fourth and fifth years, reinforcement of lines is generally insufficient. Instead of only expanding the lines' capacity with excessively high cost, the power company is willing to install DGs, which contribute to further decrease of the total profits of the power company.

B. Multi-investor Mode With Fixed Unit NUC

In the multi-investor planning mode, the power company is responsible for ensuring the system transmission capacity, i.e., the reinforcement of lines. Profits of the power company mainly come from NUC and electricity sales revenue other than P2P transactions. In this case, the unit NUC is set as 50 yuan/MW. Prosumers are able to invest and operate DGs. The selling price of DGs is set as the same for each prosumer, and the goal is to maximize the economic operation profits of the power company. Profit and cost of the power company are shown in Table III while the corresponding fifth planning result could be seen in Fig. 4.

Table III shows that NUC charged by the power company is positively correlated with load growth because the unit price

TABLE II
SINGLE-INVESTOR PLANNING RESULTS

Description	1 st year	2 nd year	3 rd year	4 th year	5 th year
Electricity sales of power company (yuan)	1.42×10^7	1.71×10^7	1.99×10^7	2.27×10^7	2.55×10^7
Cost of purchasing electricity (yuan)	1.22×10^7	1.48×10^7	1.74×10^7	1.88×10^7	2.14×10^7
Cost of lines expansion (yuan)	0	0	3.00×10^5	4.50×10^5	9.00×10^5
Cost of DGs' operation (yuan)	0	0	0	4.03×10^5	4.27×10^5
Cost of DG installation (yuan)	0	0	0	1.18×10^5	1.25×10^5
Profit of PC (yuan)	2.00×10^6	2.19×10^6	2.02×10^6	1.89×10^6	1.57×10^6

TABLE III
VIRTUAL P2P TRANSACTION INTEGRATED EXPANSION PLANNING OF DISTRIBUTION NETWORK

Description	1 st year	2 nd year	3 rd year	4 th year	5 th year
NUC (yuan)	1.48×10^6	1.78×10^6	2.08×10^6	2.37×10^6	2.67×10^6
Cost of lines (yuan)	0	0	0	1.50×10^5	3.00×10^5
Profit of PC (yuan)	1.48×10^6	1.78×10^6	2.08×10^6	2.22×10^6	2.37×10^6

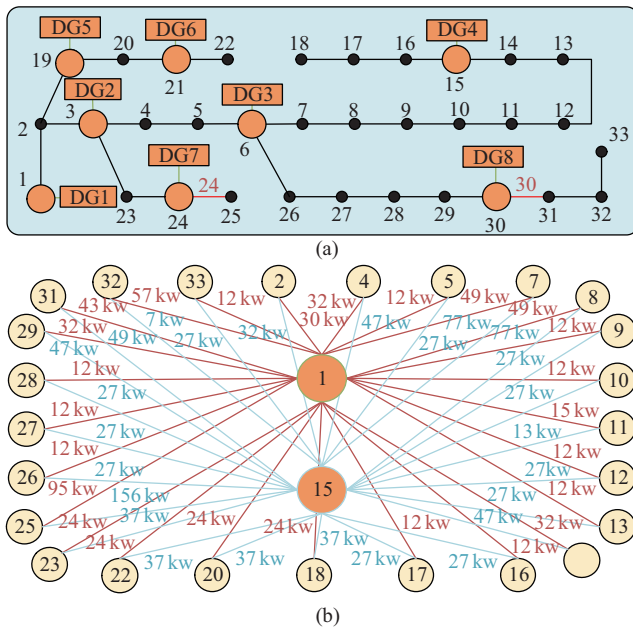


Fig. 4. Expansion planning result of multi-investor mode with fixed unit NUC in fifth year, and the P2P transactions between prosumer 1, 15 and electricity users at a time slot. (a) Expansion planning result of multi-investor mode with fixed unit NUC in fifth year. (b) The P2P transactions between prosumer 1, 15 and electricity users at a time slot.

of NUC is fixed. Investment of power company in lines is effectively reduced, which shows that DGs can effectively alleviate reinforcement pressure of the lines in the distribution network.

Compared with Tables I and II, in the first and second years, when the system load increases by 25% and 50%, respectively, the existing distribution network can meet the load demand without reinforcement of lines or installation of DGs. Since the objective is set as maximizing profits of the power company, total profit obtained by the single-investor, i.e., the local power company, from power sales is approximately 25% higher than when the NUC is charged with a fixed unit price. Given the unit profit of power sales is 100 yuan/MW and the unit profit of NUC is 30 yuan/MW, as with the growth of load, the lines' load rate in the distribution network increases, resulting in more network loss.

In the third, fourth, and fifth years, as with load growth, the profits of the power company in the multi-investor planning mode gradually exceed that in the single mode. The reason is that prosumers collectively pay the investment and operation cost of DGs. Increased load is absorbed locally, lines to be reinforced by the power company are reduced, and cost of reinforcement of lines is reduced by 60%.

C. Multi-investor Mode With Fixed Unit NUC and Different Rate_m

Considering users are more inclined to choose lower priced electricity of prosumers in P2P transactions, prosumers are more inclined to choose users with higher quotations for transactions, and the power company needs to ensure the system has a certain margin for safe operation. Based on case B, this case selects load data of the distribution network in the fifth year and simulates it in virtual P2P transactions with different participation rates. Simulation results are shown in Figs. 5 and 6.

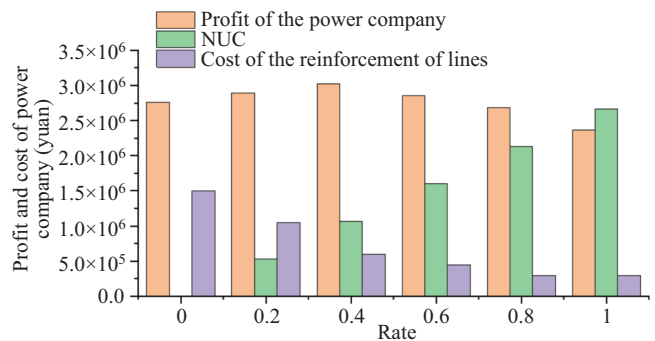


Fig. 5. Profit of power company in multi-investor mode with fixed unit NUC and different participation rates.

As shown in Fig. 5, with increase of $rate_m$ from 0 to 1, the cost of reinforcement of lines paid by the power company decreases, while the NUC charged by the power company increases linearly, which is positively correlated with $rate_m$. Total profits of the power company increased first and then decreased. When $rate_m$ grows from 0 to 0.4, increase in the total profits of the power company is mainly caused by reduction of the cost of reinforcement of lines, which is higher

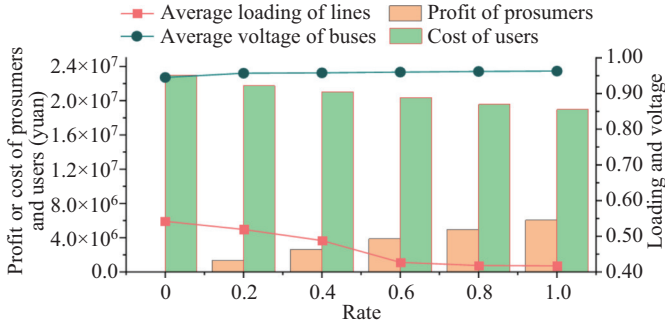


Fig. 6. Profit or cost of prosumers and users and operation performance of the distribution network in multi-investor mode with fixed unit NUC and different participation rates.

than the decrease in profits because the NUC is lower than the profits from power sales. When $rate_m$ ranges from 0.6 to 1, the total profits of the power company decreased mainly because the reduction of the cost of reinforcement of lines is lower than that due to the lower NUC, compared with the profits from power sales. It also indicates that when the investment and operation cost is large, the power company may get profits by adopting a multi-investor mode with a certain market share of P2P transactions.

As shown in Fig. 6, as $rate_m$ increases from 0 to 1, electricity consumption cost of users and the average loading rate of lines decrease, and profit of prosumers and bus voltage increase. The DGs installed by prosumers alleviates the risk of low bus voltage at the tail end of the distribution network and can effectively improve average bus voltage of the distribution network. With increase of $rate_m$, even if the number of lines needed to be reinforced in the distribution network decreases, as with the average loading rate of transmission lines. Thus, local load consumption can be effectively promoted by P2P transactions while improving the economic operation performance of the whole system.

D. Multi-investor Mode With DLMP Based NUC and Different Rate m

In this case, DLMP is used to calculate the NUC, electricity price, and power sales revenue of prosumers. The number of expanded lines is the same as in case C. Simulation results are shown in Fig. 7.

As seen from Fig. 7, as $rate_m$ increases from 0 to 1, the total cost of users decreases, the profit of prosumers first increases and then decreases, and the profit of power company gradually decreases from 0 to 0.6. When $rate_m$ is 0.8 and 1.0, the profit of the power company increases.

Compared with case C, the differences are as follows:

1) Although users' cost decreases in Fig. 7, the overall cost of users is higher than the fixed electricity price by using DLMP. When $rate_m$ increases from 0.2 to 0.6, the profits of prosumers increase. When $rate_m$ is 0.8 and 1.0, the profit of prosumers is lower than in the mode with fixed NUC. When $rate_m$ is low, the profit of the power company is not as much as with fixed NUC. When $rate_m$ is high, profit of the power company exceeds that with fixed NUC. The reason is that the main factor affecting NUC is the loading rate of

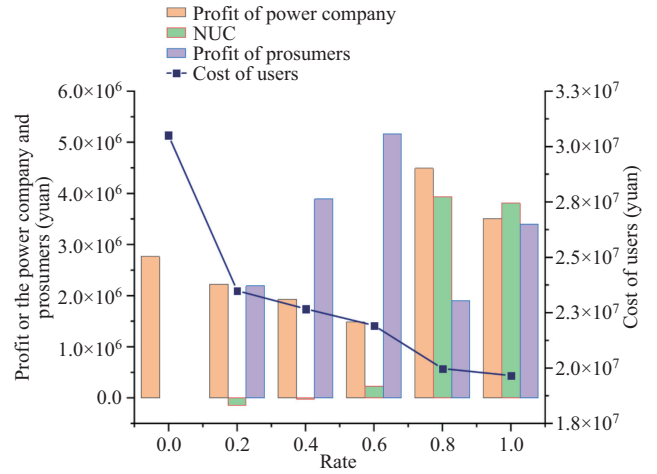


Fig. 7. Profit or cost of the power company and prosumers in multi-investor mode with different participate rates of P2P transaction driven by DLMP.

the lines. The degree of system congestion is affected by two aspects. On one hand, the DGs of prosumers could effectively reduce the load rate of lines of distribution networks. On the other hand, the P2P trading strategy mentioned above aggravate congestion of lines for promoting the willingness of electricity users to buy cheaper electricity. When $rate_m$ increases from 0 to 0.6, the NUC is small or even negative, the emergence of negative NUC shows that DLMP can adjust the P2P transactions and then regulate power flow distribution of the distribution network. Negative NUC will encourage and promote regulation of transactions to the safe operation of distribution networks.

2) When $rate_m$ increases from 0 to 0.6, profit of the power company decreases because power sales revenue decreases, and the NUC is relatively small. Integration of a small amount of DGs can alleviate congestion of lines of the distribution network and improve average voltage, the power company promotes these P2P transactions that can improve safe operation of distribution networks by NUC. In that way, it seems to be equivalent to transfer parts of the power company's profit to the prosumers.

3) When $rate_m$ is 0.8 and 1.0, with a large number of DGs, P2P transactions in the energy market become more intense. Prosumers with lower power sale prices would have more power transactions, as with paying more NUC to the power company. It is conducive to orderly competition among prosumers while maintaining safe operation of the distribution network.

V. CONCLUSION

A virtual P2P transaction integrated expansion planning method of the distribution network with DGs is proposed to the deal. A virtual P2P transaction is introduced to stimulate the trading vitality of DGs and electricity users in the electricity market. Two investment modes are designed and discussed. Single-investor, i.e., the local power company, expands the lines or DGs to meet the load growth and keep safe operation of distribution networks. In multi-investor mode, DGs are invested by prosumers while the power company is responsible

for reinforcement of the lines. Test case results show that, the power company could make more profits through the multi-investor planning framework, in the case of large expansion cost and P2P transactions with a certain participation rate. While meeting load growth, costs of electricity users, and the expansion capacity of the distribution network can be reduced by P2P transactions. The indicator DLMP is able to regulate those electricity transactions that may block the lines by charging higher NUC, and help balance interests between the power company and prosumers.

REFERENCES

- [1] N. Shang, Y. Ding, and W. Q. Cui, "Review of market power assessment and mitigation in reshaping of power systems," *Journal of Modern Power Systems and Clean Energy*, vol. 10, no. 5, pp. 1067–1084, Sep. 2022.
- [2] T. Jiang, Z. W. Shen, X. L. Jin, R. F. Zhang, A. Parisio, and X. Li, "Solution to coordination of transmission and distribution for renewable energy integration into power grids: an integrated flexibility market," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 2, pp. 444–458, Mar. 2023.
- [3] H. Gao, F. Zhang, Y. Xiang, S. Ye, X. Liu and J. Liu, "Bounded rationality based multi-VPP trading in local energy markets: a dynamic game approach with different trading targets," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 1, pp. 221–234, Jan. 2023.
- [4] Y. K. Liu, L. Wu and J. Li, "A two-stage peer-to-peer energy trading model for distribution systems with participation of utility," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 5, pp. 893–902, Sept. 2021.
- [5] S. X. Zhang, Y. C. Fang, H. Zhang, H. Z. Cheng, and X. Wang, "Maximum hosting capacity of photovoltaic generation in SOP-based power distribution network integrated with electric vehicles," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 11, pp. 8213–8224, Nov. 2022.
- [6] V. F. Martins and C. L. T. Borges, "Active distribution network integrated planning incorporating distributed generation and load response uncertainties," *IEEE Transactions on Power Systems*, vol. 26, no. 4, pp. 2164–2172, Nov. 2011.
- [7] X. Xiao, F. Wang, M. Shahidehpour, Y. Zhai and Q. Zhou, "Peer-to-Peer trading in distribution systems with the utility's operation," *CSEE Journal of Power and Energy Systems*, vol. 10, no. 2, pp. 629–638, Mar. 2024.
- [8] S. Y. Su, C. N. Lu, R. F. Chang, and G. Gutiérrez-Alcaraz, "Distributed generation interconnection planning: a wind power case study," *IEEE Transactions on Smart Grid*, vol. 2, no. 1, pp. 181–189, Mar. 2011.
- [9] L. L. Wang, Q. Zhou, Z. Xiong, Z. Zhu, C. W. Jiang, R. N. Xu, and Z. Y. Li, "Security constrained decentralized peer-to-peer transactive energy trading in distribution systems," *CSEE Journal of Power and Energy Systems*, vol. 8, no. 1, pp. 188–197, Jan. 2022.
- [10] S. F. Santos, D. Z. Fitiwi, A. W. Bizuayehu, M. Shafie-khah, M. Asensio, J. Contreras, C. M. P. Cabrita, and J. P. S. Catalão, "Impacts of operational variability and uncertainty on distributed generation investment planning: a comprehensive sensitivity analysis," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 2, pp. 855–869, Apr. 2017.
- [11] F. F. Shen, Q. W. Wu, X. L. Jin, B. Zhou, C. B. Li, and Y. Xu, "ADMM-based market clearing and optimal flexibility bidding of distribution-level flexibility market for day-ahead congestion management of distribution networks," *International Journal of Electrical Power & Energy Systems*, vol. 123, pp. 106266, Dec. 2020.
- [12] Z. X. Li, J. L. Wan, P. F. Wang, H. L. Weng, and Z. H. Li, "A novel fault section locating method based on distance matching degree in distribution network," *Protection and Control of Modern Power Systems*, vol. 6, no. 1, pp. 20, Jun. 2021.
- [13] J. C. Olivares-Rojas, E. Reyes-Archundia, J. A. Gutiérrez-Gnecchi, I. Molina-Moreno, J. Cerda-Jacobo, and A. Méndez-Patiño, "A transactive energy model for smart metering systems using blockchain," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 5, pp. 943–953, Sep. 2021.
- [14] P. L. Du, Z. Chen, Y. X. Chen, Z. W. Ma, and H. Ding, "A bi-level linearized dispatching model of active distribution network with multi-stakeholder participation based on analytical target cascading," *IEEE Access*, vol. 7, pp. 154844–154858, Oct. 2019.
- [15] M. F. Chen, M. C. Xia, and Q. F. Chen, "Research on distributed source-load interaction strategy considering energy router-based active distribution network," *IEEE Access*, vol. 7, pp. 150505–150516, Oct. 2019.
- [16] R. Li, W. Wang, and M. C. Xia, "Cooperative planning of active distribution system with renewable energy sources and energy storage systems," *IEEE Access*, vol. 6, pp. 5916–5926, Dec. 2017.
- [17] P. H. Nguyen, W. L. Kling, and P. F. Ribeiro, "A game theory strategy to integrate distributed agent-based functions in smart grids," *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 568–576, Mar. 2013.
- [18] M. Moradipoor, M. P. Moghaddam, and M. R. Haghifam, "A flexible distribution system expansion planning model: A dynamic bi-level approach," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 5867–5877, Nov. 2018.
- [19] D. N. Liu, Y. Gao, W. Y. Wang, and Z. X. Dong, "Research on bidding strategy of thermal power companies in electricity market based on multi-agent deep deterministic policy gradient," *IEEE Access*, vol. 9, pp. 81750–81764, Jun. 2021.
- [20] M. Caramanis, E. Ntakou, W. W. Hogan, A. Chakraborty, and J. Schoene, "Co-optimization of power and reserves in dynamic T&D power markets with nondispatchable renewable generation and distributed energy resources," *Proceedings of the IEEE*, vol. 104, no. 4, pp. 807–836, Apr. 2016.
- [21] J. Kim and Y. Dvorkin, "A P2P-dominant distribution system architecture," *IEEE Transactions on Power Systems*, vol. 35, no. 4, pp. 2716–2725, Jul. 2020.
- [22] M. Khorasany, Y. Mishra, and G. Ledwich, "A decentralized bilateral energy trading system for peer-to-peer electricity markets," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 6, pp. 4646–4657, Jun. 2020.
- [23] H. J. Gao, J. Y. Liu, Z. B. Wei, and Y. C. Su, "A bi-level robust planning model of active distribution network and its solution method," *Proceedings of the CSEE*, vol. 37, no. 5, pp. 1389–1400, Mar. 2017.
- [24] P. Andrianesis, M. Caramanis, R. D. Masiello, R. D. Tabors, and S. Bahramirad, "Locational marginal value of distributed energy resources as non-wires alternatives," *IEEE Transactions on Smart Grid*, vol. 11, no. 1, pp. 270–280, Jan. 2020.
- [25] K. A. Joshi and N. M. Pindoriya, "Case-specificity and its implications in distribution network analysis with increasing penetration of photovoltaic generation," *CSEE Journal of Power and Energy Systems*, vol. 3, no. 1, pp. 101–113, Mar. 2017.
- [26] A. Garces, "A linear three-phase load flow for power distribution systems," *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 827–828, Jan. 2016.
- [27] S. H. Dolatabadi, M. Ghorbanian, P. Siano, and N. D. Hatziaargyriou, "An enhanced IEEE 33 bus benchmark test system for distribution system studies," *IEEE Transactions on Power Systems*, vol. 36, no. 3, pp. 2565–2572, May 2021.
- [28] Gurobi. [Online]. 2022–01–22. Available: www.gurobi.com



Jiakun Dai received a B.S. degree from Sichuan University, China, in 2017. Currently, he is currently working toward an M.S. degree in Electrical Engineering at Sichuan University, Chengdu, China. His research interests include distributed energy integration and distribution network planning.



Yue Xiang received B.S. and Ph.D. degrees from Sichuan University, China, in 2010 and 2016, respectively. Currently, he is an Associate Professor at the College of Electrical Engineering, Sichuan University, China. His main research interests are power system planning and optimal operations, renewable energy integration and smart grids.



Yongtao Guo received a B.S. degree in Electrical Engineering from Guangxi University, Nanning, China, 2020. He is currently working toward an M.S. degree in Electrical Engineering with Sichuan University, Chengdu, China. His research interests include optimal operation and planning of integrated energy systems.