Optimal planning method of renewable distributed generation for multiple prosumers participating in distribution networks

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Abstract. In the situation that distribution system operator (DSO) and multiple prosumers jointly invest distributed generation (DG) in the distribution network, it is difficult to achieve the balance of multi-agents interests under the requirements of security operation and privacy protection. To solve this problem, an optimal planning method of DG for multiple prosumers participating in distribution networks is proposed. First, the DG planning model of DSO and prosumers are constructed separately, and the network tariff dynamic updating strategy is proposed for the optimal guidance of multi-agent collaborative planning. Then, based on the collaborative planning framework for distributed autonomous decision-making of prosumers and the global coordination of DSO, a distributed solution method is proposed. Finally, the effectiveness of the proposed method is proved through the simulation results, the experiment proves that the network tariff updating strategy can better guide the multi-agent DG collaborative planning, and has better effects in balancing the benefit of prosumers and DSO.

1. Introduction

Nowadays, with the advancement of market mechanism and DG technology, the traditional electricity users are transforming into new prosumers invested by the third-party social capitals and capable of self-generation [1]. In this situation, DG planning in distribution network is transformed from the independent responsibility of DSO into a new situation with the multi-agents participation. The joint participation of multiple prosumers in DG planning is conducive to optimizing planning resources, but how to balance the interests of multi-agents under the decentralized investment is the difficulty.

At present, researchers have conducted research on the optimal allocation of DG. The DG planning considering one investment agents has been fully investigated [2-5]. In the literature [2], a stochastic DG investment planning model is proposed and optimized from the DSO’s perspective. The authors in [3] developed a DG planning model, in which DSO optimizes the investment in DG and carried out demand response of consumers simultaneously. With the advancement of market-oriented reforms, researches on the DG planning considering multiple investment agents have gradually been carried out. In the literature [4], the calculation model for the optimal grid-connected DG capacity is proposed to maximize the benefits of DSO and DG investors. The collaborative planning method based on overall rationality in the above-mentioned literature cannot consider the different interests of each agent [6]. Pursuing the overall interests of the distribution network may lead to the decline of individual interests.
DG planning method considering multi-agent collaborative strategy has been studied [7-8]. In the literature [7], a two-level planning method for DG and distribution network is proposed. The upper and lower levels consider the planning benefit of DG and DSO, respectively. The above-mentioned literatures analyze multi-agent planning considering individual rationality. Considering the non-linearity and exponential increase in the scale of decision variables, the centralized method reduces the efficiency, and it is difficult to adapt to the demands of autonomous decision-making [9]. Several literatures solve the optimization problem with distributed algorithm [10-11]. Considering the energy management strategy between DSO and microgrids, the authors in [10] proposes a decentralized optimization method based on the alternative directional multiplier method (ADMM). However, the current study on the multi-agent distributed planning problem is very limited.

Motivated by the aforementioned research gap, this paper explores the multi-agent collaborative relationship, and proposes an optimal planning method of renewable DG for multiple prosumers participating in distribution networks. The primary contributions of the work presented are threefold:

1) Considering the joint DG planning of DSO and prosumers, a collaborative planning framework for autonomous decision-making of multi-prosumers and global coordination of DSO is proposed.

2) Dynamic network tariffs are proposed to ensure full recovery of investment costs of DSO and guide the multi-stakeholders optimal investment process.

3) An ADMM-based decentralized updating method is adopted for the dynamic update of network tariffs between multi-prosumers and DSO, and the DG planning problem is further solved.

2. Multi-agent planning model in distribution network

In the competitive market environment, DSO and multiple prosumers jointly implement the planning and operation of DG in distribution network. The collaborative planning framework is shown in Figure 1. DSO invests in a certain number of DGs, and sells electricity to users. As the independent stakeholders, multiple prosumers invest in DG within their jurisdiction and sell electricity to other users in distribution network. The prosumers use the distribution lines which belong to DSO for electricity transaction. Considering the construction and maintenance cost recovery of the lines, DSO charges network tariffs from prosumers, which is a quadratic function of the exchanged power between prosumer and DSO. First, the planning models for DSO and prosumers are established.

![Multi-agent collaborative planning frame.](image)

Figure 1. Multi-agent collaborative planning frame.

2.1. Planning modelling of prosumers

As a new type of electricity user in the distribution network, the prosumer is an independent stakeholder composed of traditional loads, multiple types of DGs and other resources. The prosumer is responsible for the planning and operation of DG within its jurisdiction. The objective of the prosumer
is to maximize its own planning and operating objectives. The decision variable is the internal DG installed capacity. The type of DG is wind turbine generation (WTG).

From the perspective of economy, for the prosumer \(i \in \Omega_{PR}\), \(\Omega_{PR}\) is the set of prosumers in distribution network, the objective of prosumer planning model is expressed by the annual comprehensive revenue \(C^{PR}\). \(C^{PR}\) includes the electricity sales revenue \(C^{PR}_{PR,S}\), DG investment costs \(C^{PR}_{PR,Inv}\), DG operation and maintenance costs \(C^{PR}_{PR,OM}\), network tariffs paid to DSO for the cost recovery of distribution lines \(C^{PR}_{PR,W}\), and government subsidies for renewable DG \(C^{PR}_{PR,C}\). The planning decision variables are \(x^{PR,DG}_{i}\) and \(N^{PR,DG}_{i}\), which are 0-1 variables. \(x^{PR,DG}_{i}\) means that whether the internal DGs are installed by prosumer \(i\), and \(N^{PR,DG}_{i}\) is the installed number of DGs in \(i\)-th prosumer’s premises.

\[
\begin{align*}
\min \quad & C^{PR}(x^{PR,DG}_{i}, N^{PR,DG}_{i}) = \frac{d(1+d)^n}{(1+d)^n-1} \cdot C_{DG}(x^{PR,DG}_{i}, N^{PR,DG}_{i}) + \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{n} \gamma^{DG}_{s,t} \cdot P^{PR,DG}_{s,i} \\
\text{subject to:} & \quad N_{i,min} \leq N^{PR,DG}_{i} \leq N_{i,max} \\
& \quad 0 \leq P^{PR,DG}_{s,i} \leq P^{PR,DG}_{s,i} \cdot PRate \\
& \quad \lambda^{W}_{s,i,t} \leq \lambda^{W}_{max}
\end{align*}
\]

where \(s\) is the scenario identifier, \(S\) is the set of scenarios in the planning period, and \(t\) is the time. \(\lambda^{S}_{s,t}\) is the price of electricity sold by prosumer \(i\) to other users at time \(t\) in scenario \(s\). \(P^{PR}_{s,i}\) is the outgoing power of prosumer \(i\) in scenario \(s\). \(P^{PR,DG}_{s,i}\) is the power generated by the internal DG of prosumer \(i\) in scenario \(s\) at time \(t\). \(P^{PR,L}_{s,i}\) is the load power of prosumer \(i\) in scenario \(s\) at time \(t\). \(d\) is the discounting rate. \(n\) is the operation years of DG. \(C_{DG}\) is the construction cost of DG. \(\gamma^{DG}\) is the unit maintenance cost of DG. \(\alpha\) and \(\beta\) are the quadratic and primary terms of the conversion coefficient of the network tariffs charged by the DSO, respectively. \(\lambda^{W}_{s,i,t}\) is the network tariff optimal variable of prosumer \(i\) in scenario \(s\) at time \(t\). \(\omega^{DG}\) is the unit government subsidies revenue. The installed DG capacity limit is introduced by Eq. (2). Equation (3) indicates DG output should not exceed the installed capacity. Equation (4) denotes network tariffs should not exceed the government limit.

2.2 Planning modelling of DSO

DSO is responsible for the DG planning of the distribution network beyond multiple prosumers. The objective is to maximize the DG planning and operation benefits within its jurisdiction. From the perspective of economy, the objective is expressed by the annual comprehensive revenue \(C^{ADN}\). \(C^{ADN}\) includes the energy purchased costs \(C^{ADN}_{B}\), electricity sales revenue \(C^{ADN}_{S}\), DG investment costs \(C^{ADN}_{Inv}\), DG operation and maintenance costs \(C^{ADN}_{OM}\), line loss costs \(C^{ADN}_{L}\), network tariffs charged from multiple prosumers \(C^{ADN}_{W}\), and government subsidies for renewable DG \(C^{ADN}_{C}\). The planning decision variables are \(x^{ADN,DG}_{i}\) and \(N^{ADN,DG}_{i}\), which are 0-1 variables. \(x^{ADN,DG}_{i}\) means that whether the DGs are invested at node \(i\), and \(N^{ADN,DG}_{i}\) is the installed number of DGs at node \(i\).
\[
\begin{align*}
\min C^{ADN}(x_i^{ADN, DG}, N_i^{ADN, DG}) &= \frac{d(1+d)^y}{(1+d)^y-1} \sum_{j \in \Phi} C_{DG}(x_i^{ADN, DG}, N_i^{ADN, DG}) + \sum_{s=1}^{S} \sum_{t=1}^{T} \lambda_{s,t}^M P_{s,t}^M + \sum_{r=1}^{R} \sum_{s=1}^{S} \lambda_{s,t}^S P_{s,t}^{loss} \\
&+ \sum_{s=1}^{S} \sum_{t=1}^{T} P_{s,t}^{ADN, DG} - \sum_{s=1}^{S} \sum_{t=1}^{T} P_{s,t}^{W, DG} - \sum_{s=1}^{S} \sum_{t=1}^{T} P_{s,t}^{PR, DG} - \sum_{s=1}^{S} \sum_{t=1}^{T} \lambda_{s,t}^S (P_{s,t}^I - \sum_{r=1}^{R} P_{s,t}^{PR}) \\
&\text{subject to:} \\
N_i^{min} &\leq N_i^{ADN, DG} \leq N_i^{max} \\
0 &\leq P_{s,t}^{ADN, DG} \leq P_i^{rate} \\
\sum_{j \in \Phi} [P_{s,ijkl} - (I_{s,ijkl})^2 r_{ijkl}] &= \sum_{j \in \Phi} P_{s,ijkl} - P_{s,ijkl}^{ADN, DG} - P_{s,ijkl}^{min} - P_{s,ijkl}^{max} + P_{s,ijkl}^{L, s} \\
\sum_{j \in \Phi} [Q_{s,ijkl} - (I_{s,ijkl})^2 x_{ijkl}] &= \sum_{j \in \Phi} Q_{s,ijkl} - Q_{s,ijkl}^{ADN, DG} - Q_{s,ijkl}^{min} - Q_{s,ijkl}^{max} + Q_{s,ijkl}^{L, s} \\
(V_{s,t})^2 &- (V_{s,t})^2 = 2(r_y P_{s,ijkl} + x_y Q_{s,ijkl}) - (I_{s,ijkl})^2 [(r_y)^2 + (x_y)^2] \\
(V_{s,t})^2 &= (I_{s,ijkl})^2 + (Q_{s,ijkl})^2 \\
V^min &\leq V_{s,t} \leq V^max \\
0 &\leq I_{s,ijkl} \leq I_{s,ijkl}^{max}
\end{align*}
\]

where $\Phi_i$ is the set of DG candidate investment node. $\lambda_{s,t}^M$ is the main grid TOU price. $P_{s,t}^{L, s}$ is the electricity purchased from main grid at time $t$ in scenario $s$. $P_{s,t}^{loss}$ is the electricity loss. $P_{s,t}^{L, s}$ is the load demand. Equation (6) indicates that the installed capacity of DG at node $i$ should not exceed the limitation. Equation (7) indicates that the output of DG should not exceed the installed capacity in prosumer $i$. Constraints (8)-(10) represent the DistFlow model to describe the power flows in the radial distribution network. The voltage and current limitation are introduced by the constraint (11).

3. Network tariff updated-based distributed optimization approach

3.1. Network tariff dynamic update strategy

Traditionally, the unified and fixed network tariff is difficult to coordinate the interests of multiple prosumers. A network tariff dynamic update strategy is proposed for the optimal guidance of multi-agent collaborative planning. Considering the multi-agent relationship and security constraints, DSO globally coordinates the exchanged power with multiple prosumers. Based on the deviation between DSO’s expected exchanged power and the prosumer’s actual exchanged power, the network tariff is dynamically updated, and further guides the planning and operation strategies of multiple prosumers.

When DSO’s expected exchanged power is greater than the prosumer’s actual exchanged power, DSO expects the prosumer to increase its DG installed capacity and further increase its DG output to meet its own optimization plans. In this situation, DSO reduces the network tariff optimal variables, and thus the network tariffs that the prosumer needs to pay decrease. Furthermore, the prosumer tends to invest more DGs with the increased profits. Based on the optimal guidance of network tariff dynamic update strategy, the planning plans of DSO and multiple prosumers tend to be consistent.

3.2. Distributed optimization approach

The multi-agent collaborative planning in distribution network is not an integral optimization problem, but several optimization sub-problems. First, the multi-agent collaborative planning framework for autonomous decision-making for multiple prosumers and global coordination of DSO is constructed. Prosumers make distributed autonomous decision-making on the internal DG planning and operation strategy aiming to maximize their self-interests. Then, DSO globally coordinates the decision-makings.
of the prosumers. Then a distributed solution method based on ADMM is proposed. The planning problem is decomposed into DSO’s planning sub-problem and prosumers’ planning sub-problems.

3.2.1. Prosumers’ planning sub-problem. Based on the prosumer’s planning model proposed in Section 2.1, the objective and constraints of prosumer $i$’s planning sub-problem is expressed as:

$$
\min \{ C_i^{PR} (x_i^{PR, DG}, N_i^{PR, DG}) \} = -C_i^{PR} - C_i^{inv} + C_i^{OM} + \\
\sum_{s=1}^{S} \sum_{l=1}^{24} \lambda_{s, i}^{W}(k) \cdot (\alpha \cdot (P_{s, i}^{PR})^2 + \beta \cdot P_{s, i}^{PR}) + \sum_{s=1}^{S} \sum_{l=1}^{24} \rho \left( P_{s, i}^{PR} \right)^2
$$

s.t. Eq. (2)-(4)

where $\rho$ is the penalty factor, $\tilde{P}_{s, i}^{PR}$ is the introduced auxiliary variable, which represents DSO’s expected exchanged power with prosumer $i$, and $\lambda_{s, i}^{W}$ is the Lagrangian multiplier.

For privacy protection, the information exchanged is limited to the exchanged power and network tariff optimal variable $\lambda_{s, i}^{W}$. In the $k+1$th iteration, the exchanged power $P_{s, i}^{PR}$ and auxiliary variables $\tilde{P}_{s, i}^{PR}(k)$ are used as coupling variables of distributed optimization to guide each prosumer to optimize its planning sub-problems. Based on $\tilde{P}_{s, i}^{PR}(k)$ and $\lambda_{s, i}^{W}(k)$ shared by DSO, each prosumer solves its planning sub-problems in parallel, and then updates DG planning strategy and exchanged power.

3.2.2. DSO’s planning sub-problem. Based on the DSO’s planning model proposed in Section 2.2, the objective and constraints of DSO’s planning sub-problem is expressed as:

$$
\min \{ C_i^{ADN} (x_i^{ADN, DG}, N_i^{ADN, DG}) \} = -C_i^{ADN} - C_i^{inv} + C_i^{B} + C_i^{L} + C_i^{OM} - \\
\sum_{s=1}^{S} \sum_{l=1}^{24} \lambda_{s, i}^{W}(k) \cdot (\alpha \cdot (\tilde{P}_{s, i}^{PR})^2 + \beta \cdot \tilde{P}_{s, i}^{PR}) + \sum_{s=1}^{S} \sum_{l=1}^{24} \gamma \left( \tilde{P}_{s, i}^{PR} - P_{s, i}^{PR}(k+1) \right)^2
$$

s.t. Eq. (6)-(11)

where $\gamma$ is the penalty factor. In the $k+1$th iteration, based on the coupling variables $P_{s, i}^{PR}(k+1)$ shared by prosumer $i$ in the $k$th iteration, DSO solves the DSO’s planning sub-problem. The DG planning strategy $N_i^{ADN, DG}(k+1)$ and output power charged by DSO is optimized and updated. Moreover, DSO is responsible for coordinating multiple prosumers’ autonomous planning and operation strategy. The expected exchanged power is shared considering constraints and multi-agent coordination relationship.

After DSO’s planning sub-problem, the network tariff optimal variable $\lambda_{s, i}^{W}$ is updated based on the deviation between the origin and the auxiliary variable of exchanged power in the $k+1$ iteration.

$$
\lambda_{s, i}^{W}(k+1) = \lambda_{s, i}^{W}(k) - \delta \tilde{P}_{s, i}^{PR}(k) - P_{s, i}^{PR}(k)
$$

where $\delta$ is the update coefficient of the Lagrange multiplier. The optimal guidance of multi-agent collaborative planning is achieved based on the dynamic update of the network tariff, and the prosumer’s actual power exchange with distribution network is as consistent as possible with DSO’s expected value. Subsequently, the $\tilde{P}_{s, i}^{PR}(k+1)$ and $\lambda_{s, i}^{W}(k+1)$ are fed back to the prosumer as known quantities for the next iteration. The iterative convergence criterion of the solution method is

$$
\left\| P_{s, i}^{PR}(k+1) - \tilde{P}_{s, i}^{PR}(k+1) \right\|_2 + \left\| \tilde{P}_{s, i}^{PR}(k+1) - \tilde{P}_{s, i}^{PR}(k) \right\|_2 \leq \varepsilon
$$

where $\varepsilon$ is the upper tolerance limit of the residual, which is a sufficiently small constant.
4. Case study
A modified IEEE 33-bus test system is used to validate the effectiveness of the proposed model and algorithm. Prosumers access at \{15, 24, 31\}. The candidate access location of DG are \{10, 19, 26\}. The system’s topology is shown in Figure 2. The reference voltage is 12.66kV.

![Wiring diagram of simulation system](image)

Figure 2. Wiring diagram of simulation system.

To verify the effectiveness of the proposed multi-agent collaborative planning method and its effect in terms of improving the economic benefits, this paper considers two different investment strategies. Strategy 1: The distribution network DG planning without multi-agent collaboration, the network tariff is charged based on the fixed optimal variable $\lambda_{W1} = 1.15$. Strategy 2: The distribution network DG planning with multi-agent collaboration, which is the proposed network tariff dynamic updated-based multi-agent collaborative planning method. The planning results of the two strategies are shown in Table 1. The net income of multiple prosumers and DSO are shown in Table 2.

| Strategy    | Node (DG installed number) | DSO  | prosumer 1 | prosumer 2 | prosumer 1 |
|-------------|----------------------------|------|------------|------------|------------|
| Strategy 1  | 10(46), 19(45), 26(49)    | 15(35)| 24(36)     | 31(36)     |            |
| Strategy 2  | 10(45), 19(43), 26(47)    | 15(42)| 24(45)     | 31(48)     |            |

Table 1. DG capacity planning results.

| Strategy | Costs and benefits/(*104 ¥) |
|----------|-----------------------------|
|          | $C^1_{PR}$ | $C^2_{PR}$ | $C^3_{PR}$ | $C_{DSO}$ | $C_{SUM}$ |
| Strategy 1 | 64.87      | 70.55       | 74.95       | 393.72    | 604.09    |
| Strategy 2 | 73.48      | 84.85       | 96.66       | 381.52    | 636.51    |

Table 2. Net income of DSO and prosumers.

It can be seen from Table 2 that the net income of DSO in Strategy 2 has dropped by 12.2*10^4 ¥ compared to Strategy 1. However, the net income of the three prosumers have increased by RMB 8.61*10^4 ¥, 14.3*10^4 ¥, 21.71*10^4 ¥respectively. The sum of net income has increased by 32.42*10^4 ¥. This is because the multi-agent collaborative planning is not considered in Strategy 1, its objective is merely to maximize the benefits of DSO, and the network tariff charged is relatively high. Therefore, strategy 1 achieves the optimal planning results of DSO, it sacrifices the interests of multiple prosumers. As an independent market participant, it is impossible for prosumers to sacrifice their own interests in order to maximize the overall benefits of DSO. This mandatory planning scheme will reduce the enthusiasm of prosumer’s participation in the market. In Strategy 2, based on the network tariff dynamic updating strategy, the multi-agent planning plan is coordinated and the multi-agents planning and operation plan achieves a balance of benefits. This method is more in line with the basic principles of the market, and it takes into account the interests of all market participants.
In order to verify the effectiveness of the algorithm proposed in this article, Figure 3 shows the dynamic update process of network tariff optimal variables of prosumer 1 and 2. Figure 3 shows that in the iterative process, the network tariff optimal variables dynamically update with the difference of coupling variables, which are the representative of DSO and prosumers’ expected strategy. Finally, the coupling variables gradually become consistent, and the network tariffs converge. Therefore, the network tariffs are updated based on the difference between DSO and prosumer’s expected strategy. Based on the network tariff dynamic updating strategy, the multi-agent collaborative DG planning combination is achieved. It can be seen from Figure 3 that the proposed distributed optimization algorithm achieves convergence after iterating to the 10th to 15th time. The planning strategies stays constant, and the difference of the coupling variables meets the iterative convergence criterion.

5. Conclusions
In the scenario where DSO and multiple prosumers jointly invest the DG in distribution network, this paper proposes a multi-agent DG collaborative planning model and a distributed planning solution method. With the participation of prosumers, the planning resources in distribution network has been optimized, the overall benefits of the multi-agent DG planning are improved. Although the proposed method reduces the DSO’s benefit, the network tariffs payed by prosumers and the reduction in network loss compensate for the benefit damage. Based on the network dynamic updating strategy, the optimal guidance for multi-agent collaborative planning is implemented, the investment cycle of the distribution network is delayed, and the balance of multi-agent benefits is achieved.

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References
[1] N. Liu, M. Cheng, X. Yu, J. Zhong and J. Lei 2018 Energy-Sharing Provider for PV Prosumer Clusters: A Hybrid Approach Using Stochastic Programming and Stackelberg Game IEEE Transactions on Industrial Electronics 65(8) 6740-6750
[2] S. F. Santos et al 2017 Novel multi-stage stochastic DG investment planning with recourse IEEE Transactions on Sustainable Energy 8(1) 164-178
[3] C. Dang, X. Wang, X. Wang, F. Li and B. Zhou 2018 DG planning incorporating demand flexibility to promote renewable integration IET Generation, Transmission & Distribution 12(20) 4419-4425
[4] M. Jooshaki, H. Farzin, A. Abbaspour, M. Fotuhi-Firuzabad and M. Lehtonen 2020 A Model for Stochastic Planning of Distribution Network and Autonomous DG Units IEEE
Transactions on Industrial Informatics 16(6)3685-3696

[5] G. Muñoz-Delgado, J. Contreras and J. M. Arroyo 2015 Joint Expansion Planning of Distributed Generation and Distribution Networks IEEE Transactions on Power Systems 30(5) 2579-2590

[6] B Zeng, J Shi, J Wen et al 2017 A game-theoretic framework for active distribution network planning to benefit different participants under the electricity market Turkish Journal of Electrical Engineering & Computer Sciences 25(1) 83-94

[7] Y Gao, X Hu, W Yang et al 2017 Multi-Objective Bilevel Coordinated Planning of Distributed Generation and Distribution Network Frame Based on Multiscenario Technique Considering Timing Characteristics IEEE Transactions on Sustainable Energy 8(4) 1415-1429

[8] H. Wang and J. Huang 2016 Cooperative Planning of Renewable Generations for Interconnected Microgrids IEEE Transactions on Smart Grid 7(5) 2486-2496

[9] D. K. Molzahn, F. Dörfler, H. Sandberg et al 2017 A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems IEEE Transactions on Smart Grid 8(6) 2941-2962

[10] H Gao, J Liu, L Wang et al 2018 Decentralized Energy Management for Networked Microgrids in Future Distribution Systems IEEE Transactions on Power Systems 33(4) 3599-3610

[11] M Xie, X Ji, X Hu, et al 2018 Autonomous optimized economic dispatch of active distribution system with multi-microgrids Energy 9(4) 2574-2594