frontiers | Frontiers in Energy Research

ORIGINAL RESEARCH
published: 26 May 2022
doi: 10.3389/fenrg.2022.902891

Multi-Stage Expansion Planning of Distribution Network Considering Distributed Power Generation

Qingjie Wang[1,2] and Ma Jing[1]*

[1]Department of Electric and Electronic Engineering, North China Electric Power University, Beijing, China, [2]State Grid Corporation of China, Beijin, China

With the gradual increase in the penetration rate of distributed power sources, in view of the planning problem of coordinating the location and capacity of distributed power sources with the grid frame and transformers of the distribution network, a distribution network that takes into account distributed power sources is proposed. Aiming at the lowest cost of investment, maintenance, energy production, energy loss, and load loss penalty, and considering the power flow constraints, planning and operation constraints of each planning stage, a multi-stage expansion planning model for the distribution network is established. The mixed-integer linear programming algorithm is used to solve the problem, and the optimal planning scheme at each stage is obtained. The simulation results show that the multi-stage expansion planning method for coordinating distributed power and distribution network proposed in this paper can prevent the problems of isolated nodes and transmission nodes, improve the reliability of the planning scheme, and have good economic benefits.

Keywords: distributed generation, distribution network planning, multi-stage, planning model, planning scheme

Edited by:
Chaolong Zhang, Anqing Normal University, China

Reviewed by:
Yin Yao, Shanghai University of Electric Power, China
Nan Yang, China Three Gorges University, China

Correspondence:
Ma Jing
3466673668@qq.com

Specialty section:
This article was submitted to Smart Grids, a section of the journal Frontiers in Energy Research

Received: *23 March 2022*
Accepted: *12 April 2022*
Published: *26 May 2022*

Citation:
Wang Q and Jing M (2022) Multi-Stage Expansion Planning of Distribution Network Considering Distributed Power Generation. Front. Energy Res. 10:902891. doi: 10.3389/fenrg.2022.902891

1 INTRODUCTION

With the deterioration of the environment and the continuous change of the energy structure (National Development and Reform Commission, 2015; Mansor and Levi, 2018; Nikoobakht et al., 2020), the penetration of Distributed Generation (DG) is gradually increasing (Afraz et al., 2019; Borghei and Ghassemi, 2021). This means that the distribution network structure as well as the power supply mode has changed (Alarcon et al., 2020; Vahidinasab et al., 2020). On the one hand, the planning results of distributed power supply and distribution network will affect each other, and it is difficult to achieve the overall optimum for a single separate planning. This will affect the planning economy and reliability (Cattani et al., 2020; Shahbazi et al., 2021a). On the other hand, for medium-term and long-term distribution network planning, its construction works are often divided into multiple stages, which are reasonably adjusted according to the changes in load. A single-stage planning model makes it difficult to take into account future load changes and the impact of distributed power sources (Franco, 2016). Therefore, it is necessary to coordinate and unify the siting and capacity of distributed power with the planning of the distribution network's grid and transformers. And it is important to study a multi-stage coordinated planning method of distribution network taking into account distributed power sources.

There are a lot of research on distribution network planning problems (Saeed and Mahmud, 2018; Koutsoukis and Georgilakis, 2019; Faria et al., 2020; Delarestaghi et al., 2021; Mojtahedzadeh et al., 2021). The author in Liu et al. (2019) takes into account the volatility of DG output and establishes a

DG siting and capacity model with the minimum risk of distribution network operation as the objective function. Narimani et al. (2018) use Monte Carlo for simulation and introduces delayed option theory for planning the multiple uncertainties of load as well as tariff in incremental distribution network planning. Jooshaki et al. (2020) considers the impact of DG on the distribution network grid structure and optimizes the lines, DG locations, and capacity of the distribution network in the distribution network planning process, but ignores the coordination between DG and the distribution network. In response to the above problems, Akbari and Moghaddam (2020) proposes to construct a fuzzy planning of distribution network grid considering DG output uncertainty. It coordinates the interaction between DG and the distribution network grid. Hemmati et al. (2015) considers the uncertainty of load and price in the electricity market environment. In the paper, a coordination and expansion planning model of distribution network and DG is proposed and the model is solved by particle swarm optimization algorithm. Muoz -Delgado et al. (2014) considered several alternatives for the installation or replacement of DGs, feeders, and transformers, and proposed a joint expansion planning model for DGs and distribution networks. The results show that incorporating distributed generation investments into the distribution network problem can significantly reduce investment costs. However, these models involve only one planning phase. In the actual planning process, construction projects are often divided into multiple stages. If a single-stage planning model is used, it is difficult to take into account future load changes and the impact of distributed power sources, and lacks an integrated layout for long-term investment strategies.

To address the multi-stage planning problem, the Tabares et al. (2015); Xing et al. (2016) considered line, substation, and distributed power supply renewal replacement and proposed a multi-stage planning model of distribution network with mixed integer linear programming. However, relatively little attention has been paid to the issue of joint expansion. The author in Masoumi-Amiri et al. (2021) propose a multi-stage planning model for active distribution networks considering the load level by using a clustering algorithm for multi-stage division of the source-load timing characteristics. And it increases the penetration of distributed power and the reliability of the system. Xiao et al. (2020) proposes an active distribution network multi-stage two-level planning model. The paper presents the boundary conditions for the most multi-stage planning with operationally constrained cases. The model improves the economics of the investment as well as the reliability of the actual operation. Shahbazi et al. (2021b) use the idea of multi-stage planning for the siting of distributed power sources and distribution grids and for the expansion of the grid. The paper improves the convergence speed of model solving by using the improved genetic membrane algorithm. However, it ignores the expansion decision of distributed generation and focuses the study on the impact of distributed power expansion on distribution investment deferral instead of solving the optimization problem of the joint expansion planning model.

To address the problems of existing research, this paper proposes a multi-stage planning method for distribution networks that considers distributed power sources. This paper establishes a multi-stage expansion planning model for distribution networks. The model aims to minimize the cost of investment, maintenance, energy production, energy loss and loss of load penalties and consider the tidal constraints, planning and operational constraints for each planning stage. The model is solved using a mixed integer linear programming algorithm to obtain the optimal planning solution for each stage. At the end of the article, the economics and effectiveness of the proposed method are verified by simulation examples.

2 DISTRIBUTION NETWORK COORDINATION PLANNING MODEL

2.1 Objective Function

The distribution network planning model aims at minimizing the total cost F. The objective function mainly includes investment cost c_t^I, maintenance cost c_t^M, production cost c_t^E, energy loss cost c_t^R and penalty cost c_t^U. The details are as follows:

$$\min\ F = \sum_{t\in T} \frac{(1+i)^{-t}}{i} c_t^I + \sum_{t\in T} \left[(1+i)^{-t} \left(c_t^M + c_t^E + c_t^R + c_t^U \right) \right] + \frac{(1+i)^{-n_T}}{i} \left(c_{n_T}^M + c_{n_T}^E + c_{n_T}^R + c_{n_T}^U \right) \quad (1)$$

Where, T is the set of planning stages; i is the annual interest rate; n_T is the number of planning stages; c_t^I is the investment cost; $c_t^E, c_t^M, c_t^R, c_t^U$ are the cost of energy production, maintenance, losses and penalties at stage t, respectively; $c_{n_T}^E, c_{n_T}^M, c_{n_T}^R, c_{n_T}^U$ are the cost of energy production, maintenance, losses and penalties for the time planning phase n_T, respectively.

2.1.1 Investment Costs

Investment costs for all stages include replacement and new feeder costs, reinforcement of existing substations and new substation costs, new transformer costs, and distributed power costs. The formula is shown below:

$$c_t^I = \sum_{l\in\{NRF,NAF\}} \left(i(1+i)^{\eta^l} \right) \Big/ \left((1+i)^{\eta^l} - 1 \right) \sum_{k\in K^l} \sum_{(s,r)\in\}\Upsilon^l} C_k^{I,l} l_{sr} x_{srkt}^l + \left(i(1+i)^{\eta^{SS}} \right) \Big/ \left((1+i)^{\eta^{SS}} - 1 \right) \sum_{s\in\Omega^{SS}} C_s^{I,SS} x_{st}^{SS} + \left(i(1+i)^{\eta^{NT}} \right) \Big/ \left((1+i)^{\eta^{NT}} - 1 \right) \sum_{k\in K^{NT}} \sum_{s\in\Omega^{SS}} C_k^{I,NT} x_{skt}^{NT} + \sum_{p\in P} \left(i(1+i)^{\eta^p} \right) \Big/ \left((1+i)^{\eta^p} - 1 \right) \sum_{k\in K^p} \sum_{s\in\Omega^p} C_k^{I,p} \lambda \bar{G}_k^p x_{skt}^p \quad (2)$$

Where, K^l, K^{NT}, K^p are the set of new feeders, transformers and distributed power sources that can be constructed, respectively; Ω^{SS}, Ω^p are collection of substations and distributed power supplies; $\}\Upsilon^l$ is the set of feeder types l, where feeder type L: $\{EFF, REF, NRF, NAF\}$ represent existing feeders, replaceable feeders, new replaceable feeders and new feeders; $C_k^{I,l}, C_s^{I,SS}, C_k^{I,NT}, C_k^{I,p}$ are the investment cost factors for feeders, substations, transformers and distributed power sources, respectively; l_{sr} is the length of the feeder *sr*; $x_{srkt}^l, x_{st}^{SS}, x_{skt}^{NT}, x_{skt}^p$ are 0–1 variables and it is used to indicate whether decision feeders, substations, transformers and distributed power supplies are constructed; λ is the system power factor; $\bar{G}_k^p$ is the rated capacity of generator *k*.

2.1.2 Maintenance Costs

Maintenance costs in all stages include feeder, transformer and generator maintenance costs. This is shown in **Equation 3**

$$c_t^M = \sum_{l\in L}\sum_{k\in K^l}\sum_{(s,r)\in\}\Upsilon^l} C_k^{M,l} y_{srkt}^l + \sum_{tr\in TR}\sum_{k\in K^t}\sum_{s\in\Omega^{SS}} C_k^{M,tr} y_{skt}^{tr} + \sum_{p\in P}\sum_{k\in K^p} \times \sum_{s\in\Omega^p} C_k^{M,p} y_{skt}^p \quad (3)$$

Where, TR is the transformer type, where $TR = \{ET, NT\}$ represent existing transformers and new transformers respectively; P is the type of generator set, where $P = \{C, W\}$ represent conventional units and distributed wind turbines respectively; $C_k^{M,l}, C_k^{M,tr}, C_k^{M,p}$ are the maintenance cost factors for feeders, generators and transformers; $y_{srkt}^l, y_{skt}^{tr}, y_{skt}^p$ are 0–1 variables and these variables are used to make decisions about feeder, transformer and generator operating conditions.

2.1.3 Energy Production Costs

Energy production costs for each stage include energy production conversion costs for substations and distributed power sources and determined by **Equation 4**

$$c_t^E = \sum_{b\in B}\Delta_b\lambda\left(\sum_{tr\in TR}\sum_{k\in K^{tr}}\sum_{s\in\Omega^{SS}} C_b^{SS} g_{sktb}^{tr} + \sum_{p\in P}\sum_{k\in K^p}\sum_{s\in\Omega^p} C_k^{E,p} g_{sktb}^p\right) \quad (4)$$

Where, B is the set of load levels; Δ_b is the duration of the load level *b*; $C_b^{SS}, C_k^{E,p}$ are the cost coefficients of energy supply for substations and generating units; $g_{sktb}^{tr}, g_{sktb}^p$ are the currents injected into node *s* by the transformer and generator set, respectively.

2.1.4 Energy Loss Costs

Energy loss costs include energy loss costs for transformers and feeders. The specific calculation of energy loss cost is shown in **Equation 5**

$$c_t^R = \sum_{b\in B}\Delta_b C_b^{SS}\lambda\left[\sum_{tr\in TR}\sum_{k\in K^{tr}}\sum_{s\in\Omega^{SS}} Z_k^{tr}\left(g_{sktb}^{tr}\right)^2 + \sum_{l\in L}\sum_{k\in K^i}\sum_{(s,r)\in\}\Upsilon^l} Z_k^l l_{sr}\left(f_{srktb}^l + f_{rsktb}^l\right)^2\right] \quad (5)$$

Where, C_b^{SS} is the energy loss cost factor of the substation; Z_k^{tr}, Z_k^l are the impedance of the transformer and the unit impedance of the feeder; g_{sktb}^{tr} is the current injected into node *s* by the transformer; f^l_{srktb} is the current in the feeder *sr*.

2.1.5 Penalty Costs

Penalty costs include those incurred by generators and substations when they fail to meet load demand. The penalty cost is calculated by **Equation 6**

$$c_t^U = \sum_{b\in B}\sum_{s\in\Omega_t^{LN}} \Delta_b C^U \lambda d_{stb}^U \quad (6)$$

Where, C^U is the penalty cost factor and d_{stb}^U is the unsatisfied load of node *s*.

2.2 Constraint Conditions

2.2.1 Flow Constraint

The flow constraint is used to constrain the operating state of the system to ensure the normal operation of the system, and the relevant constraint equation is as follows.

1) Node voltage constraints

$$\underline{V} \le v_{stb} \le \bar{V} \quad \forall s \in \Omega^N, \forall t \in T, \forall b \in B \quad (7)$$

Where, a is the voltage of node s at load level b in planning stage t; b, c are the minimum and maximum values of node voltage, respectively.

2) Feeder current constraints

$$0 \le f_{srktb}^l \le y_{srkt}^l \bar{F}_k^l \quad \forall l \in L, \forall s \in \Omega_r^l, \forall r \in \Omega^N, \forall k \in K^l, \forall t \in T, \forall b \in B \quad (8)$$

Where, $\bar{F}_k^l$ is the maximum value of the current flowing through the feeder.

3) Transformer injection current constraints

$$0 \le g_{sktb}^{tr} \le y_{skt}^{tr} \bar{G}_k^{tr} \quad \forall tr \in TR, \forall s \in \Omega^{SS}, \forall k \in K^{tr}, \forall t \in T, \forall b \in B \quad (9)$$

Where, $\bar{G}_k^{tr}$ is the maximum value of transformer current injection.

4) Loss of load constraints

$$0 \le d_{stb}^U \le \mu_b D_{st} \quad \forall s \in \Omega_t^{LN}, \forall t \in T, \forall b \in B \quad (10)$$

Where, μ_b is the load factor at load level *b*; D_{st} is the maximum load demand at node *s*.

5) Unit output constraints

$$0 \le g_{sktb}^W \le y_{skt}^W \bar{G}_{sktb}^W \quad \forall s \in \Omega^W, \forall k \in K^W, \forall t \in T, \forall b \in B \quad (11)$$

Where, $\bar{G}_{sktb}^W$ is the maximum wind speed level.

6) Distributed power penetration constraints

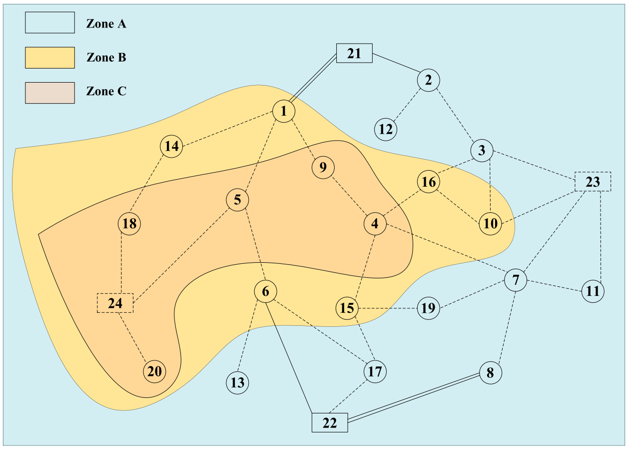

FIGURE 1 | 24 node distribution system.

TABLE 1 | Distribution network node load data.

Node	Stage/MVA			Node	Stage/MVA		
	1	2	3		1	2	3
1	5.13	4.21	6.24	11	0.00	1.53	2.64
2	0.58	0.45	1.21	12	0.00	0.96	1.36
3	2.65	3.74	4.21	13	0.00	1.14	1.87
4	0.38	0.51	2.54	14	0.00	3.09	3.15
5	0.21	0.36	0.46	15	0.00	1.63	1.62
6	1.42	0.69	1.81	16	0.00	2.17	1.24
7	4.32	3.74	4.36	17	0.00	0.00	2.48
8	0.74	0.63	0.96	18	0.00	0.00	2.17
9	1.32	1.24	1.74	19	0.00	0.00	1.82
10	1.52	2.31	2.41	20	0.00	0.00	3.74

$$\sum_{p\in P}\sum_{k\in K^P}\sum_{s\in\Omega^P} g^p_{sktb} \le \xi \sum_{s\in\Omega^{LN}_t} \mu_b D_{st} \quad \forall t\in T, \forall b\in B \tag{12}$$

Where, ξ is the upper limit of penetration of distributed generation.

7) Node current balance constraints

$$\sum_{l\in L}\sum_{k\in K^1}\sum_{r\in\Omega^l_s}\left(f^l_{srktb} - f^l_{rsktb}\right) = \sum_{tr\in TR}\sum_{k\in K^{tr}} g^{tr}_{sktb} + \sum_{p\in P}\sum_{k\in K^P} g^p_{sktb} - \mu_b D_{st} + d^U_{stb} \quad \forall s\in\Omega^N, \forall t\in T, \forall b\in B \tag{13}$$

8) Feeder state constraints

$$y^l_{srkt}\left[Z^l_k l_{sr} f^l_{srktb} - (v_{stb} - v_{rtb})\right] = 0 \quad \forall l\in L, \forall s\in\Omega^l_r, \forall r\in\Omega^N, \forall k\in K^l, \forall t\in T, \forall b\in B \tag{14}$$

Where, v_{stb}, v_{rtb} are the voltage amplitudes at node s and node r, respectively.

TABLE 2 | Branch data.

Branch		l_{sr}/km	Branch		l_{sr}/km	Branch		l_{sr}/km
s	r		s	r		s	r	
1	5	2.64	4	9	1.20	7	23	0.90
1	9	1.25	4	15	1.60	8	22	1.90
1	14	1.25	4	16	1.30	10	16	1.60
1	21	2.64	5	6	2.40	10	23	1.30
2	3	2.00	5	24	0.70	11	23	1.60
2	12	1.10	6	13	1.20	14	18	1.00
2	21	1.70	6	17	2.20	15	17	1.20
3	10	1.10	6	22	2.70	15	19	0.80
3	16	1.20	7	8	2.00	17	22	1.50
3	23	1.20	7	11	1.10	18	24	1.50
4	7	2.60	7	19	1.20	20	24	0.90

TABLE 3 | Wind speed for each area in the three stages.

Zone	Wind speed/(m/s)		
	1	2	3
A	9.44	10.36	11.25
B	5.32	8.47	7.36
C	4.69	6.21	5.97

2.2.2 Planning and Operational Constraints

In this paper, **Eqs. 15–18** are line, substation, transformer, and distributed power supply construction constraints and these constructions allow up to one reinforcement, replacement or new construction; **Eq. 19** is a new transformer constraint to ensure that new transformers can only be added to previously expanded or constructed substations; **Eqs. 20–22** are the constraints on the use of the feeder, which determine the direction of the current; **Eqs. 23, 24** are the new transformers and distributed generators put into operation constraints; **Eq. 25** is the investment constraint for each stage. The construction program for each stage, the timing as well as the number of lines, substations, transformers, and distributed power sources shall meet the following constraints:

$$\sum_{t\in T}\sum_{k\in K^l} x^l_{srkt} \le 1 \quad \forall l\in\{NRF, NAF\}, \forall (s,r)\in\}\Upsilon^l \tag{15}$$

$$\sum_{t\in T} x^{SS}_{st} \le 1 \quad \forall s\in\Omega^{SS} \tag{16}$$

$$\sum_{t\in T}\sum_{k\in K^{NT}} x^{NT}_{skt} \le 1 \quad \forall s\in\Omega^{SS} \tag{17}$$

$$\sum_{t\in T}\sum_{k\in K^P} x^p_{skt} \le 1 \quad \forall p\in P, \forall s\in\Omega^P \tag{18}$$

$$x^{NT}_{skt} \le \sum_{\tau=1}^{t} x^{SS}_{s\tau} \quad \forall s\in\Omega^{SS}, \forall k\in K^{NT}, \forall t\in T \tag{19}$$

$$y^{EFF}_{srkt} + y^{EFF}_{rskt} \le 1 \quad \forall (s,r)\in\}\Upsilon^{EFF}, \forall k\in K^{EFF}, \forall t\in T \tag{20}$$

TABLE 4 | Related parameters of DG to be selected and conventional units.

	Type	Capacity/MW	Construction costs/(million yuan/MW)	Maintenance costs/(yuan/MWh)
Wind Turbines	1	1	130	300
	2	2	120	280
Conventional Units	1	0.95	1120	50
	2	2.25	1100	50

TABLE 5 | Related parameters for candidate transformers units.

Transformer type	Capacity/MW	Impedance/Ω	Investment costs/million yuan	Maintenance costs/yuan
1	12	0.16	450	1200
2	15	0.13	600	1500

$$y_{srkt}^{l} + y_{rskt}^{l} \le \sum_{\tau=1}^{t} x_{srk\tau}^{l} \quad (21)$$
$$\forall l \in \{NRF, NAF\}, \forall (s,r) \in \}\Upsilon^{l}, \forall k \in K^{l}, \forall t \in T$$

$$y_{srkt}^{ERF} + y_{rskt}^{ERF} \le 1 - \sum_{\tau=1}^{t} \sum_{\kappa \in K^{NRF}} x_{sr\kappa\tau}^{NRF} \quad (22)$$
$$\forall (s,r) \in \}\Upsilon^{ERF}, \forall k \in K^{ERF}, \forall t \in T$$

$$y_{skt}^{NT} \le \sum_{\tau=1}^{t} x_{sk\tau}^{NT} \quad \forall s \in \Omega^{SS}, \forall k \in K^{NT}, \forall t \in T \quad (23)$$

$$y_{skt}^{p} \le \sum_{\tau=1}^{t} x_{sk\tau}^{p} \quad \forall p \in P, \forall s \in \Omega^{p}, \forall k \in K^{p}, \forall t \in T \quad (24)$$

$$\sum_{l \in \{NRF, NAF\}} \sum_{k \in K^{l}} \sum_{(s,r) \in \}\Upsilon^{l}} C_{k}^{I,l} l_{sr} x_{srkt}^{l} + \sum_{s \in \Omega^{SS}} C_{s}^{I,SS} x_{st}^{SS} + \sum_{k \in K^{NT}} \times \sum_{s \in \Omega SS} C_{k}^{I,NT} x_{skt}^{NT} + \sum_{p \in P} \sum_{k \in K^{p}} \sum_{s \in \Omega^{p}} C_{k}^{I,p} \lambda \bar{G}_{k}^{p} x_{skt}^{p} \le IB_{t} \quad (25)$$

Where, IB_t is the investment budget for stage t; $\}\Upsilon^{l}$ is the set of feeder types l, where feeder type L: $\{EFF, REF, NRF, NAF\}$ represent existing feeders, replaceable feeders, new replaceable feeders and new feeders; l_{sr} is the length of the feeder sr; $x_{srkt}^{l}, x_{st}^{SS}, x_{skt}^{NT}, x_{skt}^{p}$ are 0–1 variables and it is used to indicate whether decision feeders, substations, transformers and distributed power supplies are constructed.

3 SIMULATION AND ANALYSIS

3.1 Parameter Setting

In this paper, to verify the validity of the proposed methodology, a 3-year phase planning analysis is conducted using the IEEE 24-node power distribution system. The system includes 20 load nodes, 4 substation nodes and 33 feeders, and its topology is shown in **Figure 1**. Where the system voltage level is 20 KV, the upper and lower limits of the node voltage are 0.95–1.05pu of the rated voltage, and the inflation rate is 0.05; the load data for the three stages are shown in **Table 1**, with a load power factor of 0.9 and a load cutting cost of 16 yuan/kwh; line data as shown in **Table 2**, with a feeder life of 30 years; The wind speed data for each region in the three stages are shown in **Table 3**; the parameters related to the DG to be selected and the conventional unit are shown in **Table 4**, where the positions to be selected are {1, 4, 5, 9, 15, 17, 18, 19} for the DG and {2, 3, 7, 13, 15, 16, 17, 20} for the conventional unit; the parameters of the constructed and to-be-constructed substation are shown in **Table 5**, and the cost of purchasing power from the substation is 0.49 yuan/kwh; the relevant parameters of the conductor to be selected are shown in **Table 6**.

The simulation was performed in Win10 environment with Intel(R) Core(TM) i5-7200U CPU @ 2.50GHz, running memory of 8 GB, and simulation software of MATLAB R2016b. Since the model developed is an integer linear programming model, the YALMIP & CPLEX solver is used to solve the model. Two cases are set up for comparative analysis.

Case I. distribution network expansion planning without considering distributed power sources.

Case II. Multi-stage expansion planning of distribution network considering distributed power sources (method in this paper).

3.2 Analysis of Planning Results

As can be seen in **Figure 2**, the two cases have significantly different planning results at each planning stage. The capacity of the feeder and transformer installed without distributed power is greater than the capacity of the feeder and transformer installed with distributed power. It results in larger investment costs in feeders and transformers. In the case of distributed generation, the load pressure can be effectively relieved by installing wind turbines as the load demand gradually increases. On the other hand, more distributed power sources are installed in the C zone, where wind speeds are higher, and conventional generators are mostly installed at load nodes outside the C zone.

TABLE 6 | Related parameters for candidate conductors units.

	Line type	Current limit/MVA	Impedance/(Ω/km)	Investment costs/(million yuan/km)
NRF	1	6.29	0.557	11.5
	2	9.21	0.487	18.2
NAF	1	3.96	0.731	9.1
	2	6.29	0.558	15.3

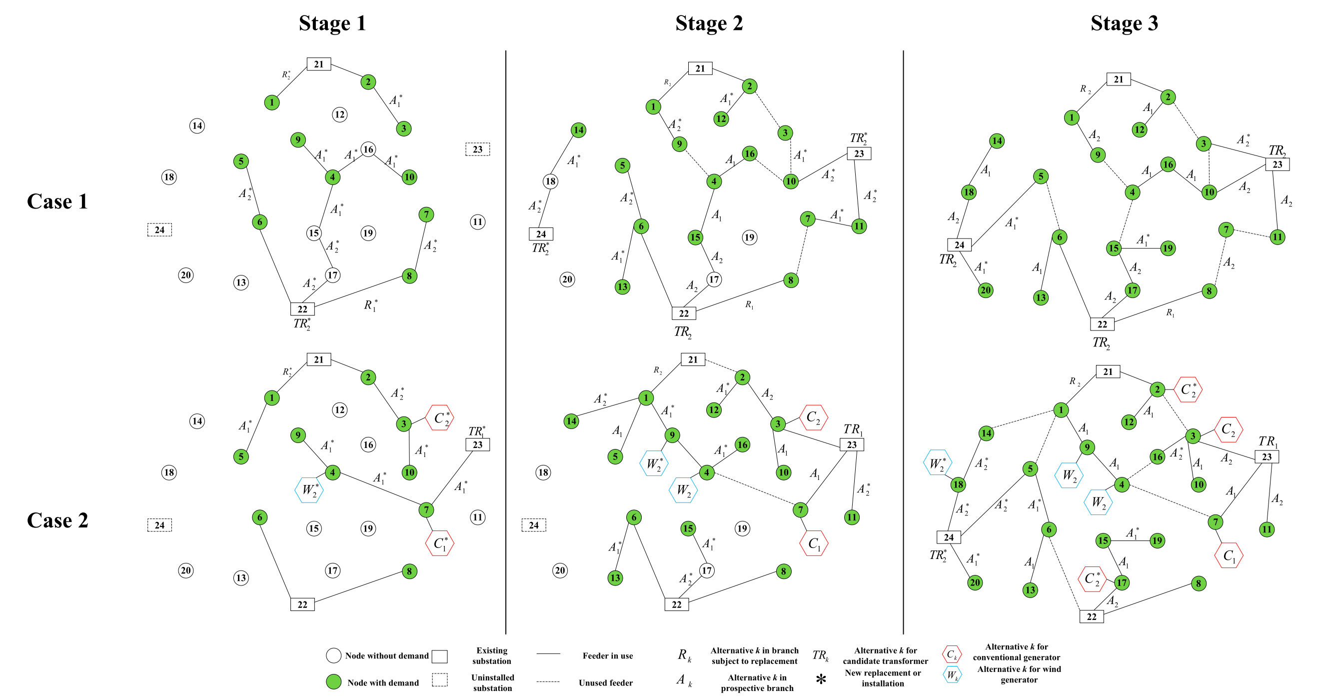

FIGURE 2 | Planning schemes for two cases.

TABLE 7 | Unit output and loss in different cases.

			Stage		
			1	2	3
Without DG	Production	Generators	0.00	0.00	0.00
		Transformers	107.54	187.36	309.97
	Losses	Generators	1.96	2.36	4.65
		Transformers	0.36	0.48	0.84
With DG	Production	Generators	26.47	52.81	76.45
		Transformers	80.54	139.74	228.54
	Losses	Generators	0.74	1.87	2.64
		Transformers	0.24	0.52	0.82

3.3 System Performance Comparison

The unit output as well as loss data for different cases are shown in **Table 7**. As can be seen in **Table 7**, the addition of distributed power sources leads to a significant reduction in the level of energy provided by the transformer located at the substation node. In addition, for Case 2, the energy losses in the feeder and transformer are lower than those in Case 1, except for the energy losses in the transformer in stage 2, which are slightly higher than those in Case 1. In stage 2, the energy provided by the transformer in Case 2 is lower compared to Case 1. However, the overall output is higher due to the distributed power supply.

TABLE 8 | Planning costs in different cases.

		Stage		
		1	2	3
Without DG	Investment cost/million yuan	8.84	16.055	6.11
	Maintenance cost/million yuan	0.065	0.13	0.13
	Production cost/million yuan	48.75	80.795	137.215
	Loss cost/million yuan	0.91	1.235	2.275
	Penalty cost/million yuan	0.00	0.00	0.00
With DG	Investment cost/million yuan	37.83	29.315	36.595
	Maintenance cost/million yuan	1.56	2.73	4.42
	Production cost/million yuan	41.665	68.51	116.675
	Loss cost/million yuan	0.455	1.04	1.495
	Penalty cost/million yuan	0.00	0.00	0.00

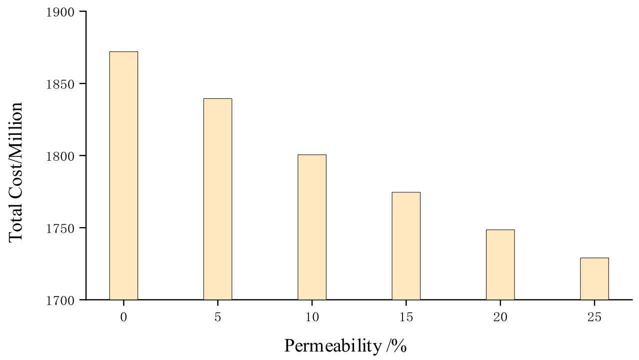

FIGURE 3 | The relationship between distributed power penetration level and total cost.

3.4 Comparison of Planning Economics

A comparison of the planning economics for different cases is shown in **Table 8**. The table shows that for Case 1 the investment cost in stage 2 is higher compared to stage 1 and stage 3. The reason for this is the construction of two new substations at nodes 23 and 24 in phase 2, including the installation of two new transformers at these nodes. But for Case 2, the biggest investment cost is during Stage 1. It is caused by the addition of substations and transformers at candidate node 23 in stage 1 and the installation of three distributed power sources at nodes 3, 4, and 7. In both cases, as load demand increases, O&M costs as well as wear and tear costs are gradually rising. It can be seen that the addition of DG makes Case 2 incur higher investment and maintenance costs compared to Case 1. However, the costs associated with energy production and energy losses are lower, resulting in more significant overall economics. The total cost is reduced by 7.55% relative to Case 1.

3.5 Analysis of Penetration Levels

Figure 3 shows the variation of the total cost for penetration levels between 0% and 25%. It can be seen that the total planning cost decreases significantly as the wind penetration level increases.

4 CONCLUSION

In this paper, the application of distributed power investment decision in multi-stage distribution expansion planning problem is studied, and a multi-stage coordinated planning method for distribution network taking into account distributed power is proposed. Simulation results show that, on the one hand, coordinating the investment decision of distributed power sources with the expansion planning of the distribution network can prevent the problems of isolated and transmission nodes. It also reduces network energy loss, thus improving the reliability of planning results. On the other hand, multi-stage planning can avoid the depreciation cost of equipment generated by overbuilding and equipment redundancy in the early stage of operation. Multi-stage planning is a more rational planning scheme based on the load demand at each planning stage and has good economic benefits.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

QW: conceptualization, methodology, software, resources, formal analysis, investigation, writing—original draft, writing—review and editing. JM: conceptualization, methodology, software, resources, formal analysis, investigation, writing—review and editing.

REFERENCES

Afraz, A., Rezaeealam, B., Seyedshenava, S., and Doostizadeh, M. (2019). Active Distribution Network Planning Considering Shared Demand Management. *Ifs* 37 (6), 8015–8028. doi:10.3233/jifs-190420

Akbari, T., and Moghaddam, S. Z. (2020). Coordinated Scheme for Expansion Planning of Distribution Networks: A Bilevel Game Approach. *IET Generation, Transm. Distribution* 14 (14), 2839–2846. doi:10.1049/iet-gtd.2019.1924

Alarcon, J. A., Santamaria, F., Al-Sumaiti, A. S., and Rivera, S. (2020). Low-Capacity Exploitation of Distribution Networks and its Effect on the Planning of Distribution Networks[J]. *Energies* 8 (63), 4562–4573. doi:10.3390/en13081920

Borghei, M., and Ghassemi, M. (2021). Optimal Planning of Microgrids for Resilient Distribution Networks. *Int. J. Electr. Power Energ. Syst.* 128 (52), 106682–106693. doi:10.1016/j.ijepes.2020.106682

Cattani, I. B., Chaparro, E., and Barán, B. (2020). Distribution System Operation and Expansion Planning Using Network Reconfiguration[J]. *IEEE Latin America Trans.* 18 (5), 845–852. doi:10.1109/tla.2020.9082912

Delarestaghi, J. M., Arefi, A., Ledwich, G., and Borghetti, A. (2021). A Distribution Network Planning Model Considering Neighborhood Energy Trading. *Electric Power Syst. Res.* 191 (26), 106894. doi:10.1016/j.epsr.2020.106894

Faria, W. R., Martins, D. d. B., Nametala, C. A. L., and Pereira, B. R. (2020). Protection System Planning for Distribution Networks: A Probabilistic Approach. *Electric Power Syst. Res.* 189 (15), 106612–106623. doi:10.1016/j.epsr.2020.106612

Franco, J. F. (2016). Multistage Long-Term Expansion Planning of Electrical Distribution Systems Considering Multiple Alternatives[J]. *IEEE Trans. Power Syst.* 31 (3), 1900–1914. doi:10.1109/tpwrs.2015.2443175

Hemmati, R., Hooshmand, R.-A., and Taheri, N. (2015). Distribution Network Expansion Planning and DG Placement in the Presence of Uncertainties. *Int. J. Electr. Power Energ. Syst.* 73, 665–673. doi:10.1016/j.ijepes.2015.05.024

Jooshaki, M., Farzin, H., Abbaspour, A., Fotuhi-Firuzabad, M., and Lehtonen, M. (2020). A Model for Stochastic Planning of Distribution Network and Autonomous DG Units. *IEEE Trans. Ind. Inf.* 16 (6), 3685–3696. doi:10.1109/tii.2019.2936280

Koutsoukis, N., and Georgilakis, P. (2019). A Chance-Constrained Multistage Planning Method for Active Distribution Networks. *Energies* 12 (21), 4154. doi:10.3390/en12214154

Liu, X., Wang, L., Wu, Y., Wei, B., and Dongyang, Q. (2019). Locating and Sizing Planning of Distributed Generation Power Supply Consid-Ering the Operational Risk Cost of Distribution Network[J]. *Trans-actions China Electrotechnical Soc.* 34 (S1), 264–271. doi:10.19595/j.cnki.1000-6753.tces.181516

Mansor, N. N., and Levi, V. (2018). Operational Planning of Distribution Networks Based on Utility Planning Concepts[J]. *IEEE Trans. Power Syst.* 34 (3), 2114–2127. doi:10.1109/tpwrs.2018.2885275

Masoumi-Amiri, S. M., Shahabi, M., and Barforoushi, T. (2021). Interactive Framework Development for Microgrid Expansion Strategy and Distribution Network Expansion Planning. *Sustainable Energ. Grids Networks* 27 (11), 100512–100526. doi:10.1016/j.segan.2021.100512

Mojtahedzadeh, S., Ravadanegh, S. N., and Haghifam, M. R. (2021). Microgrid-based Resilient Distribution Network Planning for a new town. *IET Renew. Power Gen* 15 (15), 3524–3538. doi:10.1049/rpg2.12241

Muoz-Delgado, G., Contreras, J., and Arroyo, J. M. (2014). Joint Expansion Planning of Distributed Generation and Distribution Networks[J]. *IEEE Trans. Power Syst.* 30 (5), 2579–2590. doi:10.1109/TPWRS.2014.2364960

Narimani, A., Nourbakhsh, G., Arefi, A., Ledwich, G. F., and Walker, G. R. (2018). SAIDI Constrained Economic Planning and Utilization of Central Storage in Rural Distribution Networks[J]. *IEEE Syst. J.* 13 (1), 842–853. doi:10.1109/jsyst.2018.2852630

National Development and Reform Commission (2015). Several Opin-Ions of the central Committee of the Communist Party of China and the State council on Further Deepening the Reform of the Power System (Zhong Fa[2015]No.9) [EB/OL]. Available at : http://tgs.ndrc.gov.cn/zywj/201601/20160129773852.html.

Nikoobakht, A., Aghaei, J., Massrur, H. R., and Hemmati, R. (2020). Decentralized Hybrid Robust/stochastic Expansion Planning in Coordinated Transmission and Active Distribution Networks for Hosting Large-Scale Wind Energy[J]. *IET Generation Transm. Distribution* 14 (5), 797–807. doi:10.1049/iet-gtd.2019.0888

Saeed, H., and Mahmud, F. F. (2018). Integrated Planning for Distribution Automation and Network Capacity Expansion[J]. *IEEE Trans. Smart Grid* 10 (4), 4279–4288. doi:10.1109/TSG.2018.2855218

Shahbazi, A., Aghaei, J., Pirouzi, S., Niknam, T., Shafie-khah, M., and Catalão, J. P. S. (2021). Effects of Resilience-Oriented Design on Distribution Networks Operation Planning. *Electric Power Syst. Res.* 191 (6), 106902–106915. doi:10.1016/j.epsr.2020.106902

Shahbazi, A., Aghaei, J., Pirouzi, S., Niknam, T., Vahidinasab, V., Shafie-khah, M., et al. (2021). Holistic Approach to Resilient Electrical Energy Distribution Network Planning. *Int. J. Electr. Power Energ. Syst.* 132 (5), 107212–107226. doi:10.1016/j.ijepes.2021.107212

Tabares, A., Franco, J. F., Lavorato, M., and Rider, M. J. (2015). Multistage Long-Term Expansion Planning of Electrical Distribution Systems Considering Multiple Alternatives[J]. *IEEE Trans. Power Syst.* 31 (3), 1900–1914. doi:10.1109/tpwrs.2015.2448942

Vahidinasab, V., Tabarzadi, M., Arasteh, H., Alizadeh, M. I., Mohammad Beigi, M., Sheikhzadeh, H. R., et al. (2020). Overview of Electric Energy Distribution Networks Expansion Planning. *IEEE Access* 8 (79), 34750–34769. doi:10.1109/access.2020.2973455

Xiao, X., Wang, F., Shahidehpour, M., Li, Z., and Yan, M. (2020). Coordination of Distribution Network Reinforcement and DER Planning in Competitive Market[J]. *IEEE Trans. Smart Grid* 12 (3), 12261–12271. doi:10.1109/tsg.2020.3026014

Xing, H., Cheng, H., Zhang, Y., and Zeng, P. (2016). Active Distribution Network Expansion Planning Integrating Dispersed Energy Storage Systems. *IET Generation, Transm. Distribution* 10 (3), 638–644. doi:10.1049/iet-gtd.2015.0411

Conflict of Interest: QW is working at State Grid Corporation of China, and at the same time he is a PhD student at NCEPU.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.