AC/DC Hybrid Distribution System Expansion Planning Under Long-Term Uncertainty Considering Flexible Investment

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ABSTRACT This paper presents a novel flexible multistage AC/DC distribution system expansion planning model, where the flexible investment strategy is taken into account to address the long-term development uncertainty of load demand and DG. Uncertainty is modeled through a multistage scenario tree to capture the possible system states across the planning horizon. As uncertain information revealed gradually over the planning horizon, the planning decisions at each stage are made sequentially within limited disposable reservation funds (RFs). The overall problem is formulated as a mixed-integer linear programming model that guarantees the convergence to optimality by using commercially available software. We compare the total costs of the optimal planning solutions within different proportions of RFs and analyze the flexibility value of RFs for long-term planning problems. In addition, the impact of RFs on the adjustment ability of the plans and the investment risks under uncertainty are evaluated. Case studies are carried out on an AC/DC hybrid system to validate the effectiveness of the proposed model to constitute flexible options when facing long-term uncertainty. The obtained results show the importance of reserving a suitable proportion of RFs in the planning stage, which has a significant influence on the adaptability of the planning solution to uncertain factors.

INDEX TERMS AC/DC distribution system, expansion planning, mixed-integer linear programming, flexible investment, long-term uncertainty.

NOMENCLATURE

INDICES

n Index for lines
i Index for nodes
t Index for time periods
k Index for installed equipment types
m Index for load levels
∼ Index for AC variables
− Index for DC variables

SETS

NA/NR Set of newly replacement/added equipment
ΩSS/ΩSVG/ΩVSC/ΩLA/ΩLD Set of nodes for substations, SVGs, and VSCs

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PARAMETERS

C1,SS / C1,TR Investment cost coefficients of substations, transformers, AC/DC feeders, SVGs, and VSCs
C1,LA/C1,LD/C1,SVG/C1,VSC Maintenance cost coefficients of transformers and AC/DC feeders
C1,M,TR/C1,M,LA/C1,M,LD/C1,E,SS/C1,E,DEG Cost coefficients of energy supplied by substations and DGs

ΩLL/ΩDG Set of load/DG nodes
ΩNA/ΩND Set of nodes in AC/DC system
ΩLA/ΩLA Set of feeders with node i as head/tail
ΩVSC,i Set of DC feeders connected to VSC node i
ΩLA,i Set of AC feeders connected to substation node i

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In recent years, renewable energy sources (RES) based distributed generation (DG) has proliferated rapidly in the distribution system (DS). The increasing integration of renewable DG promotes the development of DC technologies in DS, and AC/DC hybrid DS become the development trend for future DS [1]. It is necessary to propose appropriate planning approaches for the future hybrid AC/DC system. In addition, the rapid growth of RES entails significant uncertainty [2], rendering the distribution system operator (DSO) unable to obtain accurate information for long-term projects, such as the location, magnitude, and timing of DG connection to the distribution network and the load growth rate, etc. Therefore, it is essential for DSO to ensure that the AC/DC hybrid system planning decisions be flexible and adaptable concerning certain occurrences of changes in the future [3].

Traditional distribution system expansion planning (DSEP) is known as the set of strategies in determining the type, capacity, siting, and timing of the installation of new equipment, in order to satisfy the growing demand in the defined horizon [4]. Numerous studies have discussed AC DSEP problems, which is a non-convex mixed integer nonlinear problem. The methods used to solve this problem can be divided into two categories: mathematical programming methods [5]–[7] and heuristic methods [8], [9]. The mathematical methods are proved to find an optimal solution for DSEP, but its computational effort increases rapidly as the size of the problem increases [5]. The heuristic methods can be used for large-scale DSEP, but it requires high computational skill and may not find optimal solutions [8]. Actually, the performance of these two methods depends on the nature of the DSEP problem.

Nowadays, the planning of AC/DC hybrid DS has become an active research area to realize high penetrations of DC components. With respect to the modeling technique, the optimal power flow of the AC/DC hybrid system has been systematically investigated [10]–[12]. Several researchers have investigated the optimal planning of AC/DC hybrid systems and solved them using mathematical methods [13], heuristic methods [14]–[16], and combination methods of them [17]. For example, the authors of [13] presented a planning method for the design of AC/DC hybrid DS for commercial buildings and solved it using Benders decomposition technique. In [14], a conceptual AC/DC DS planning approach using a genetic algorithm (GA) that considers both low- and medium-voltage sides was developed. In [15], a stochastic AC/DC hybrid DS planning model using GA was formulated, considering the possibility of each line/bus being AC or DC. The authors of [16] proposed a multi-objective stochastic planning framework for AC/DC hybrid DS using GA, where the overall costs and reliability are both considered. In another study [17], a bi-level planning approach for AC/DC hybrid DS considering N-1 security criterion was developed, and the model was solved using a nested GA and numerical method. However, these studies above ignored the development uncertainties of load demand and DG in...
long-term AC/DC hybrid DSEP problems. In fact, the incorporation of uncertainties into the planning models is essential for obtaining optimal planning solutions in real-world DS.

In recent years, multistage DSEP under uncertainty has received considerable attention. Several uncertainty modeling techniques have been used in DSEP problems. For example, the probabilistic technique [4], [18], the stochastic optimization [5], [19], [20], and the robust optimization (RO) [7], [21]. It should be noted that the above optimization methods are limited to a static description of making planning solutions, and the investment decisions in all stages have been optimized before the realization of uncertainties [22]. That means the planning decisions over the planning horizon cannot be adjusted once they are determined. Nevertheless, the long-term DSEP is a multistage problem, and the uncertain information will be revealed gradually over the planning period. Due to the irreversible nature of such capital-intensive planning projects, there may exist a significant risk of stranded equipment or premature lock-in to sub-optimal investment paths in the case of certain scenario realizations [3], [23]. Therefore, the planning decisions should have the flexibility to be adjusted with the future uncertainty information revealed.

Several studies have discussed dynamic investment problems under uncertainty. Dynamic investment in multistage planning means the investment decisions at all stages are adjusted with uncertain information gradually revealed [23], [24]; its objective is to capture the planning decisions’ flexibility for addressing uncertainty. The real option analysis (ROA) technique is a typical method and has been applied in the DSEP problems [23], [25]. It provides a systematic framework to compare the performance of different investment strategies under uncertainty. However, this method only considers relatively limited flexibility options (defer, relocate, or abandon some equipment investment) to adjust the planning decisions and can not be used to planning problems for large systems. To overcome this problem, a planning approach combining stochastic programming and ROA is proposed [3], [22], which considers the sequential implementation process of multistage investment in the planning process. In this model, uncertainty is modeled via a scenario tree, and the planning solution is a decision tree among all the uncertain scenarios.

However, in practical DSEP projects, the planning decisions can not be adjusted without restriction, and they are limited by the amount of reservation funds (RFs). RFs are reserved for the adjustment of the planning projects, and its amount usually depends on the financial status of the planners. In fact, the problem of long-term DSEP considering dynamic investment can be viewed as a risk management problem, dynamic investment serves as a hedge against uncertain scenarios, and the amount of RFs determines the plans’ ability to resist risks. To the best of the authors’ knowledge, none of the studies in the literature has proposed a planning approach for DSEP considering dynamic investment with limited RFs. In addition, the hybrid AC/DC DS is the future form of DS, and this planning method should be applied to the AC/DC hybrid DSEP problems under long-term uncertainty.

To fulfill the mentioned gaps in the literature, this paper focuses on AC/DC hybrid DSEP problems under uncertainty considering flexible investment strategy. A multistage planning model for AC/DC hybrid DS considering dynamic investment with limited RFs are proposed, and the overall problem is formulated as a mixed-integer linear programming (MILP). The proposed approach is tested on an AC/DC hybrid system to prove its effectiveness. The main contributions of this paper can be summarized as follows:

1) Proposing the process of flexible investment on multistage DSEP under uncertainty, where the planning decisions are made sequentially within limited RFs as uncertain information revealed gradually over the planning horizon.

2) Developing a flexible planning model for AC/DC hybrid DSEP problem considering the dynamic investment strategy with limited RFs, where the installation of substations, transformers, AC/DC feeders, VSCs, SVGs are jointly considered.

3) Introducing an economic comparison between the proposed planning approach and the deterministic approach. This comparison verified the value of keeping dynamic investment strategies in long-term DSEP problems.

4) Analyzing the effect of RFs proportion on the adjustment ability of the planning solutions. The adjusted planning solutions under different proportions of RFs are compared and discussed.

The remainder of this paper is organized as follows. The planning problem and the concept of flexible investment are described in Section II. Section III presents the mathematical formulation of the proposed planning model and its solving procedure. Case studies are shown in Section IV, and Section V concludes the study of this paper.

II. PROBLEM DESCRIPTION

A. PLANNING PROBLEM DESCRIPTION

Considering the advantages of the DC system for improving power transfer capacity and accommodating DGs, widely RES distributed in remote areas can be connected through a DC system and transmitted to the AC system to provide power supply for load demand. It is a typical structure of an AC/DC hybrid DS [16], as shown in Fig.1. With the reformation of the power market and the opening of social capital, a large number of DGs investment by RES suppliers or individual users has emerged in the DS. This paper considers that the DSEP and DGs planning belong to different stakeholders. The function of the DSO is to determine the expansion plan of substations, AC/DC lines, SVGs and, VSCs with minimal cost and acceptable quality standards.

Due to the large interval of long-term DSEP problems, two uncertainty factors related to the evolution of the system are considered. The first is the deployment of the RES-based DG, which is affected by the related policies. The growth rate of load demand is another uncertain factor.
B. FLEXIBLE INVESTMENT STRATEGY IN DSEP

For a long-term DSEP problem, the dynamic planning method is usually adopted, which divides the planning period into several stages for consideration. It takes into account the multistage of project construction, the time value of capital, load forecasting, etc., making the planning result more reasonable. During the implementation stage, in order to enhance the adaptability of the planning under uncertainty, the rolling planning method is applied, which means the planning decisions at each stage will be adjusted according to the latest corresponding information.

Consider more realistic situations, a certain proportion of RFs will be reserved in the planning stage, and the RFs will be used for the adjustment of the planning solutions in the implementation stage. It is a flexible investment strategy to resist the risk, and the proportion of RFs is directly related to the adjustment of the planning solutions. Thus, in order to reduce the adverse impact of the uncertainty on the planning results, the proportion of RFs should be evaluated based on uncertain factors in the implementation stage [26].

In this paper, we focus on the long-term uncertainty related to the evolution of the loads and DG capacity. It is modeled through a multistage scenario tree [27], which captures the possible system states across the planning horizon. Let the sequence $\xi_t$ with $t = 1, \ldots, T$ be the stochastic parameters for load demand and DG capacity at each stage. As can be observed from Fig. 2, the scenario tree can be generated as follows: At each stage, through the scenario generation and reduction methods, several evolution states of $\xi_t$ can be generated, then different scenario paths across the planning horizons compose the multistage scenario tree.

Actually, the uncertain parameters $\xi_1, \ldots, \xi_T$ are revealed gradually over the implementation stage, and can not be acquired simultaneously. Thus, the flexible investment strategy with limited disposable RFs is adopted. At stage 1, the current state is definite, and the state in the last two stages are predicted, the optimal planning solution is obtained based on the optimization model. After performing the planning solutions at stage 1, stage 2 reaches a stochastically new state, e.g., $S_1$ in Fig. 2. For this new state, the subsequent planning solutions are updated within disposable RFs restrictions combining the latest information. In the next stage, the decision process is repeated similarly. By simulating the performance of the planning results among all possible scenario paths, such as the total costs, the load demand curtailment, the DG curtailment, etc., the flexibility value of RFs to deal with the uncertainty can be adequately evaluated. In addition, sensitivity analysis on the proportion of RFs can be simulated to analyze the investment risks.

III. MODEL FORMULATION AND SOLUTION METHODOLOGY

Based on the concepts of flexible investment proposed in the previous section, an AC/DC hybrid DSEP model that considers flexible investment strategy is formulated. The detailed formulation of the model is given below.

A. THE OBJECTIVE FUNCTION

According to [5], the objective of the planning model is to minimize the present value of the total costs over the planning horizon, which consist of four parts: 1) investment costs 2) maintenance costs 3) production costs and 4) unserved energy costs, as is presented in (1).

$$\min f = \sum_{t} \frac{1}{IR \cdot (1 + IR)^{-1}} (c^I_t + c^M_t + c^E_t + c^U_t)$$  \hspace{1cm} (1)$$

where:

$$c^I_t = \sum_{SS \notin \{NR, NA\}} \sum_{i \in \Omega_{SS}} (x^S_{t,i} c^I_{S,i} T_{SS} + x^T_{t,i} c^I_{T,i} T_{TR} T_{TR} T_{TR})$$

$$+ \sum_{i \in \Omega_{SVG}} x^S_{t,i} c^I_{SVG} T_{SVG}$$

$$+ \sum_{i \in \Omega_{VSC}} x^S_{t,i} c^I_{VSC} T_{VSC}$$

$$\times \sum_{LA \in \{NR, NA\}} \sum_{n \in \Omega_{LA}} \sum_{k \in \Omega_{LA}} x^L_{t,n,k} I_{k} c^I_{LA} T_{LA}$$

$$+ \sum_{n \in \Omega_{LD}} \sum_{k \in \Omega_{LD}} x^L_{t,n,k} I_{k} c^I_{LD} T_{LD}$$  \hspace{1cm} (2)$$

$$c^M_t = \sum_{SS \notin \{NR, RA\}} \sum_{i \in \Omega_{SS}} x^S_{t,i} c^M_{i}$$

$$c^E_t$$

$$c^U_t$$

FIGURE 1. Structure of AC/DC hybrid distribution network.

FIGURE 2. Scenario tree describing long-term uncertainty.
In equation (2), investment of substations, transformers, SVGs, VSCs, and AC/DC feeders are presented by their construction variables and corresponding investment costs. Equation (3) models the maintenance costs of transformers and feeders, and two binary variables, $y_{t,n,m}$ and $\bar{y}_{t,n,m}$, are used to model feeders power flow in the forward and backward direction. In (4), the production costs are formulated as the costs of electrical energy received from the upstream power grids and DGs, the discretization of demand curve into several load levels is used to characterize the load demand, which is generally accepted in long-term planning models. Equation (5) corresponds to the penalty costs of load and DG curtailment. The capital recovery rates amortize the investment costs of installed equipment over their lifecycle, as is presented in (6).

$$
\tau_\xi = \frac{IR \cdot (1 + IR)^{Y_\xi}}{(1 + IR)^{Y_\xi} - 1} \quad \xi \in \{SS, TR, SVG, VSC, LA, LD\} 
$$

(6)

B. THE CONSTRAINTS

1) INVESTMENT AND UTILIZATION CONSTRAINT

Equations (7)-(12) guarantee that the candidate equipment mentioned above is bound to exist after its construction. Note that construction variables for substations, feeders, SVGs are binary variables, whereas for transformers and VSCs are integer variables.

$$
x_{t,1,i}^{SS} \leq x_{t,i}^{SS} \quad \forall 2 \leq t \leq N_t, i \in \Omega_{SS} 
$$

(7)

$$
x_{t,1,i}^{TR} \leq x_{t,i}^{TR} \quad \forall 2 \leq t \leq N_t, i \in \Omega_{SS} 
$$

(8)

$$
x_{t,1,i,k}^{L} \leq x_{t,i,k}^{L} \quad \forall 2 \leq t \leq N_t, i \in \Omega_{LA}, k \in K_{LA} 
$$

(9)

$$
x_{t,1,i,k}^{L} \leq x_{t,i,k}^{L} \quad \forall 2 \leq t \leq N_t, i \in \Omega_{LD}, k \in K_{LD} 
$$

(10)

$$
x_{t,1,i}^{VSC} \leq x_{t,i}^{VSC} \quad \forall 2 \leq t \leq N_t, i \in \Omega_{VSC} 
$$

(11)

$$
x_{t,1,i}^{SVG} \leq x_{t,i}^{SVG} \quad \forall 2 \leq t \leq N_t, i \in \Omega_{SVG} 
$$

(12)

Equations (13)(14) are employed based on the fact that only one of the candidate alternatives can be used for AC/DC feeders over the planning horizon.

$$
\sum_{k \in K_{LD}} x_{t,n,k}^{L} \leq 1 \forall t \leq N_t, \forall n \in \Omega_{LA} 
$$

(13)

$$
\sum_{k \in K_{LD}} x_{t,n,k}^{L} \leq 1 \forall t \leq N_t, \forall n \in \Omega_{LD} 
$$

(14)

Equation (15) specifies that new transformers can only be added to the attached substations that have been previously expanded or built. The same analysis can be applied to (16)(17), where substations, VSCs and their corresponding feeders are built simultaneously. Equation (18) imposes a maximum installation number limit for SVGs at each stage.

$$
x_{t,n,k}^{TR} \leq M \cdot x_{t,n}^{SS} \quad \forall t \leq N_t, i \in \Omega_{SS} 
$$

(15)

$$
x_{t,n,k}^{SS} \leq x_{t,i}^{SS} \quad \forall t \leq N_t, i \in \Omega_{SS}, n \in \Omega_{LA}^{SS,i} 
$$

(16)

$$
x_{t,n,k}^{VSC} \leq x_{t,i,k}^{VSC} \quad \forall t \leq N_t, i \in \Omega_{VSC}, n \in \Omega_{LD}^{VSC,i} 
$$

(17)

$$
x_{t,n,k}^{SVG} \leq N_{t,n}^{SVG} \quad \forall t \leq N_t, i \in \Omega_{SVG} 
$$

(18)

2) POWER FLOW BALANCE CONSTRAINT

Equations (19)-(21) represent the AC power flow formulation in a radial distribution network based on DisFlow branch equations [28]. Equation (19) depicts the active and reactive power flows of a feeder selection to the voltages of its sending and receiving ends and the Big-M method is introduced to extend the formulation to account for the utilization states of all feeders. Note that the power losses are abandoned for relatively small values, which results in the linear formulations [6]. Finally, equation (21) defines the branch thermal constraint for the feeders.

$$
\left\{ \begin{array}{l}
\sum_{n \in \Omega_{LA}^{SS,i}} p_{t,n,m}^{L} - \sum_{n \in \Omega_{LA}^{LL,i}} q_{t,n,m}^{L} = p_{t,i,m}^{LL} + \tilde{p}_{t,1,i,m} - (s_{t,i,m}^{LL} - s_{t,1,i,m}^{LL})\phi_{t,i,m}^{LL} \\
\sum_{n \in \Omega_{LA}^{SS,i}} q_{t,n,m}^{L} - \sum_{n \in \Omega_{LA}^{LL,i}} p_{t,n,m}^{L} = q_{t,i,m}^{LL} + \tilde{q}_{t,1,i,m} + q_{t,1,i,m}^{SVG} - (s_{t,i,m}^{LL} - s_{t,1,i,m}^{LL})\phi_{t,i,m}^{LL} \\
\Delta_{t,n,m} = M \cdot (1 - x_{t,1,n,m} - y_{t,1,n,m}) \\
\tilde{u}_{t,n,m} - \tilde{u}_{t,n,m} \geq 2(p_{t,n,m}^{R} + q_{t,n,m}^{R} + q_{t,n,m}^{X}\Delta_{t,n,m}) \\
\Lambda_{t,n,m} = (q_{t,n,m}^{R} + q_{t,n,m}^{X}\Delta_{t,n,m})^{2} \leq (S_{n}^{R} + y_{t,n,m}) \forall n \in \Omega_{LA} 
\end{array} \right. 
$$

(19)

$$
\left\{ \begin{array}{l}
\sum_{n \in \Omega_{LA}^{SS,i}} p_{t,n,m}^{L} - \sum_{n \in \Omega_{LA}^{LL,i}} q_{t,n,m}^{L} = p_{t,i,m}^{LL} + \tilde{p}_{t,1,i,m} - (s_{t,i,m}^{LL} - s_{t,1,i,m}^{LL})\phi_{t,i,m}^{LL} \\
\sum_{n \in \Omega_{LA}^{SS,i}} q_{t,n,m}^{L} - \sum_{n \in \Omega_{LA}^{LL,i}} p_{t,n,m}^{L} = q_{t,i,m}^{LL} + \tilde{q}_{t,1,i,m} + q_{t,1,i,m}^{SVG} - (s_{t,i,m}^{LL} - s_{t,1,i,m}^{LL})\phi_{t,i,m}^{LL} \\
\Delta_{t,n,m} = M \cdot (1 - x_{t,1,n,m} - y_{t,1,n,m}) \\
\tilde{u}_{t,n,m} - \tilde{u}_{t,n,m} \geq 2(p_{t,n,m}^{R} + q_{t,n,m}^{R} + q_{t,n,m}^{X}\Delta_{t,n,m}) \\
\Lambda_{t,n,m} = (q_{t,n,m}^{R} + q_{t,n,m}^{X}\Delta_{t,n,m})^{2} \leq (S_{n}^{R} + y_{t,n,m}) \forall n \in \Omega_{LA} 
\end{array} \right. 
$$

(20)

Equation (21) is a quadratic circular constraint that can be linearized approximately by several square constraints [29]. On the premise of ensuring accuracy, two circumscribed square constraints are selected to overcome the nonlinearities.
The schematic diagram and formulations are as follows.

\[ F(i,n,m) + (F(i,n,m) - G(i,n,m)) \leq P_nL(i,n,m) \leq G(i,n,m) + (F(i,n,m) - G(i,n,m)) \]

\[ -S_n^L(i,n,m) \leq P_nL(i,n,m) - S_n^L(i,n,m) \leq S_n^L(i,n,m) \]

\[ -2S_n^L(i,n,m) \leq P_nL(i,n,m) - S_n^L(i,n,m) \leq 2S_n^L(i,n,m) \]

\[ \forall n \in \Omega_L \quad (22) \]

The power flow formulations in the DC system are similar to that of the AC system, which is presented in Equation (23)-(25). The difference is that feeders’ reactance and reactive power flow are out of consideration in the DC system, and the power injections from substations are substituted by DGs.

\[ \sum_{n \in \Omega_{LD}^+} P_{n,i,m} - \sum_{n \in \Omega_{LD}^-} P_{n,i,m} = P_{DG} - P_{CDG} + P_{VSC} \quad \forall i \in \Omega_{ND} \quad (23) \]

\[ \Delta_{i,m} = H(1 - \gamma_{i,n,m} - \gamma_{i,n,m}^+) \]

\[ \forall n \in \Omega_{LD} \quad (24) \]

\[ P_{n,i,m} \leq S_n^L(i,n,m) \quad \forall n \in \Omega_{LD} \quad (25) \]

3) RADIALITY CONSTRAINT

For AC systems, the networks are radially operated in view of their topologies, which are defined by the feeders’ operation variables \( \gamma_{i,n,m} \) and \( \gamma_{i,n,m}^+ \). Equation (26) guarantees that the feeders can not be operated in two directions simultaneously. Equation (27) limits the utilization of new replaced/added feeders.

\[ \gamma_{i,n,m} + \gamma_{i,n,m}^+ \leq 1 \quad \forall n \in \Omega_L \quad (26) \]

\[ \gamma_{i,n,m} + \gamma_{i,n,m}^+ \leq x_{i,n,k} \quad \forall n \in \Omega_L \quad (27) \]

The radial topology is similar to the tree structure, whereas substation nodes correspond to the parent node, and each load node has a particular parent node to ensure its power supply, as is presented in (28). Equation (29) defines the numerical relationships between the nodes and operated feeders.

\[ \begin{align*}
\sum_{n \in \Omega_{LL}^+} \gamma_{i,n,m}^+ & + \sum_{n \in \Omega_{LL}^-} \gamma_{i,n,m}^- = 1 \quad \forall i \in \Omega_{LL} \\
\sum_{n \in \Omega_{SS}^+} \gamma_{i,n,m}^+ & + \sum_{n \in \Omega_{SS}^-} \gamma_{i,n,m}^- = 0 \quad \forall i \in \Omega_{SS} \\
\sum_{n \in \Omega_{LA}^+} (\gamma_{i,n,m}^+ & + \gamma_{i,n,m}^-) = N_{\Omega NA} - N_{\Omega m} \quad (29)
\end{align*} \]

However, when the DGs power injection in the DC system is brought into play, an isolated area may exist in some circumstances. Fictitious power flow constraint (30)-(33) are considered [5], which guarantees that each nodal demand has a path for power supply from the substation. Equation (30) limits the fictitious power flows injected by fictitious substations. Equation (31) defines the fictitious demand at load nodes is equal to 1 p.u., whereas at the transfer nodes is set to 0. Equation (32) bounds the fictitious power flows of the AC feeders. Equation (33) represents the fictitious power nodal balance equation.

\[ 0 \leq s_{LL,i,m} \leq x_{SS,i} N_{\Omega NA} \quad \forall i \in \Omega_{SS} \quad (30) \]

\[ \bar{p}_{i,m} = \begin{cases} 1, & s_{LL,i,m} \neq 0 \\ 0, & s_{LL,i,m} = 0 \end{cases} \]

\[ \begin{align*}
-\bar{N}_{\Omega NA} (\gamma_{i,n,m}^+ & + \gamma_{i,n,m}^-) \\
\leq & \bar{p}_{i,m} \leq \bar{N}_{\Omega NA} (\gamma_{i,n,m}^+ & + \gamma_{i,n,m}^-) \\
\forall n \in \Omega_{LA} \quad (32)
\end{align*} \]

4) UPPER AND LOWER BOUNDARIES CONSTRAINT

Equation (34)-(36) set the upper and lower boundaries of the AC/DC nodal voltage magnitudes. Equation (36) determines the nodal demand in each load level, and Equation (37) limits the load curtailment is no more than that value. Equation (38) restrains the active, reactive power of substations within its capacity. Equation (39) defines the boundaries of reactive power compensation from SVGs. Equations (40)-(42) limit the active power, curtailment power, and minimum utilization rates of DGs.

\[ \begin{align*}
(\bar{u}_{\min}^2) & \leq \bar{u}_{i,t,m} \leq (\bar{u}_{\max}^2) \quad \forall i \in \Omega_{NA} \\
(\bar{u}_{\min}^2) & \leq \bar{u}_{i,t,m} \leq (\bar{u}_{\max}^2) \quad \forall i \in \Omega_{ND} \\
\bar{s}_{LL,i,m} & = s_{CLL,i} \bar{p}_{LL} \quad \forall i \in \Omega_{LL} \\
0 \leq & \bar{s}_{LL,i,m} \leq x_{LL,i} \bar{p}_{LL} \quad \forall i \in \Omega_{LL} \\
0 \leq & s_{LL,i,m} \leq x_{LL,i} \bar{p}_{LL} \quad (37)
\end{align*} \]

\[ \begin{align*}
0 \leq & x_{i,n,k} \bar{p}_{TR} \quad \forall i \in \Omega_{SS} \\
0 \leq & \bar{q}_{SS,i,m} \leq x_{i,n,k} \bar{p}_{TR} \sqrt{1 - \varphi_{LL}^2} \quad \forall i \in \Omega_{SS} \\
0 \leq & p^{DG}_{i,m} \leq \bar{p}_{DG} \quad \forall i \in \Omega_{DG} \quad (39) \]

\[ \begin{align*}
0 \leq & p^{DG}_{i,m} \leq \bar{p}_{DG} \quad \forall i \in \Omega_{DG} \quad (40)
\end{align*} \]
5) VSC CONSTRAINT

Equations (43)-(46) represent the VSC operation formulation between the AC and DC system. Equation (43) determines the relations of voltages, power injections in the AC- and DC-side. Equation (44) specifies the power injection of the VSC capacity constraint and negative for the DC system; this can be reflected by the power injection from VSC is positive for the AC system the VSC is limited within its rated capacity. Note that the DC-side. Equation (45)-(46) specify the power injection of the relations of voltages, power injections in the AC- and DC-side. Equation (44) determine the power injection from VSC is positive for the AC system and negative for the DC system; this can be reflected by the negative sign in (44). Similar to (22), VSC capacity constraint of active and reactive power in AC-side is defined in (46).

\[
0 \leq p^{CDG}_{t,i,m} \leq S^{DG}_{t,i} \cdot \beta_{m}^{DG} \quad \forall i \in \Omega_{DG} \quad (41)
\]

\[
\eta \cdot S_{t,i}^{DG} \cdot \beta_{m}^{DG} \leq p^{DG}_{t,i,m} + p^{CDG}_{t,i,m} \leq S_{t,i}^{DG} \cdot \beta_{m}^{DG} \quad \forall i \in \Omega_{DG} \quad (42)
\]

\[
\tilde{u}_{t} = \tilde{u}_{t} \cdot k_{VSC} \cdot \epsilon_{VSC} \quad \forall i \in \Omega_{VSC} \quad (43)
\]

\[
\tilde{p}_{t,i,m} = -p_{t,i,m} \cdot \eta \quad \forall i \in \Omega_{VSC} \quad (44)
\]

\[
-x_{t,i}^{VSC} - \sqrt{2} \tilde{x}_{i}^{VSC} \leq \tilde{p}_{t,i,m} \leq 0 \quad \forall i \in \Omega_{VSC} \quad (45)
\]

\[
0 \leq p_{t,i,m} \leq S_{t,i}^{VSC} \quad \forall i \in \Omega_{VSC} \quad (46)
\]

6) FLEXIBLE INVESTMENT CONSTRAINT

Based on the model above, the optimal planning solution under a certain scenario path can be solved. Considering the flexible investment strategy process, Equation (47)-(50) are supplemented to the model. Equation (47)(48) define the load demand and DG capacity at each stage under uncertain scenarios. It is worth noting that the factor \(l_{f}\) and \(g_{f}\) are equal to 1 in the predicted scenario. Consider the flexible investment strategy, the planning solution after stage 1 will be adjusted under different uncertain scenario paths. Equation (49) indicates that the installed equipment at stage 1 with definite information are consistent with the original plan. Equation (50) imposes the budget limit on investment costs for adjusting the planning solution after stage 1.

\[
S_{t,i}^{LL}(l_{i}) = C_{t,i}^{LL, pre} \cdot l_{f}(l_{i}) \quad \forall 2 \leq t \leq N_{i} \quad (47)
\]

\[
S_{t,i}^{DG}(l_{i}) = C_{t,i}^{DG, pre} \cdot g_{f}(l_{i}) \quad \forall 2 \leq t \leq N_{i} \quad (48)
\]

\[
x_{1}^{f} = X_{1}^{f} \quad \forall f \in \{SS, TR, L, SVG, VSC\} \quad (49)
\]

\[
\sum_{t \geq 2} C_{t,i}^{f}(l_{i}) \leq (1 + \lambda) \cdot \sum_{t \geq 2} C_{t,i}^{f} \quad (50)
\]

C. SOLVING PROCEDURE

The AC/DC hybrid DSEP model considering flexible investment strategy is formulated as a MILP for which the convergence to the global optimal solution is guaranteed and standard off-the-shelf commercially software is available [6]. Flowchart of the solution procedure is shown in Fig.4. First, the optimal planning solution under the expected scenario path is solved. Then, the model considering flexible investment strategy is solved under each uncertain scenario paths and the largest proportion of RFs to be added is obtained. Finally, a sensitivity analysis of the RFs proportion is conducted to analyze its effect on the planning solution.

IV. CASE STUDY

A. PARAMETER DESCRIPTION

To validate the proposed planning method, an AC/DC hybrid system of Fig. 5 is used to carry out numerical experiments, which consists of a 24-node AC distribution system, a 7-node
DC distribution system, and 4 candidate collection feeders. The details of the feeders’ topology parameters and peak nodal load demands can refer to [16]. The planning horizon is 15 years subdivided into three periods of 5 years. A 5% interest rate is set.

The base voltage of the AC and DC system are 20kV and 35kV, respectively. The voltage at each node is restricted to 0.95–1.05p.u. The AC system consists of 4 substations, 20 load nodes and 33 feeders, and the DC system includes 7 DG nodes and 12 candidate feeders. Four DC feeders are set to establish a connection between the AC and DC system. The load duration curve is discretized in three load levels of 70%, 83%, and 100% of peak demand, with durations of 2000 h/year, 5760 h/year, and 1000 h/year, respectively. The system load power factor is 0.9, and the load curtailment cost is 2 $ / kWh.

### TABLE 1. Parameters for feeders.

| Type  | Node | Existing Capacity (kVA) | Cost($) | Transformers’ number limit |
|-------|------|--------------------------|---------|--------------------------|
| AC(NR) | 1 | 7500 | 100000 | 2 |
| AC(NR) | 2 | 7500 | 100000 | 2 |
| AC(NA) | 1 | 7500 | 100000 | 2 |
| DC(NA) | 1 | 7500 | 100000 | 2 |

The existing feeders in the AC system correspond to the type 1 of the new replacement AC feeder in table I. For simplicity, the maintenance costs and lifecycles of all the feeders are set as 450 $/year and 25 years, respectively.

The electricity purchase cost from the superior power grid is 0.07$/kWh. The unitary capacity of the transformer is 3000kVA, the construction cost is $180000, and the main-tenance cost is 1% of it. A 30-year lifecycle is set for all transformers. The unitary capacity of SVG is 500kVar, the investment cost is $110000, and the maximum installation number at each stage is 1, 2, and 4, respectively.

In this paper, CPLEX was chosen as the optimization solver under the Yalmip toolbox in MATLAB. In order to compare the detailed total costs of the adjusted schemes under different proportions of disposable RFs, the optimality gap of MILP is set to 0.01%. Under this stopping criterion, the attainment of each solution took 20 min on average.

### B. PLANNING SOLUTION UNDER THE EXPECTED SCENARIO

The optimal planning solution in the expected scenario is presented in Case 1 of Fig. 6, and the detailed equipment installation status of the system at each stage can be observed intuitively. With the increase of load demand, substations with larger capacity and more feeders are constructed in the AC system to provide power supply for the load demand. The construction of the VSCs and connection feeders can guarantee the secure transmission of DGs’ power supply from the DC system to the AC system.

### C. PLANNING SOLUTIONS CONSIDERING DYNAMIC INVESTMENT

Consider the development uncertainty of load demand and DG deployment, six uncertain scenarios are considered for stage 2 and stage 3, with different probabilities of occurrence, as is shown in Table 6. Parameters $lf$ and $gf$ are normalized multipliers, whose basic values are the predicted load demand and the DG capacity.

### TABLE 6. Considered scenarios.

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 |
|----------|---|---|---|---|---|---|
| $lf/gf$ at stage 2 | 1/1 | 1/1.2 | 1/1.2 | 1/1 | 1/1.2 | 1/1.2 |
| $lf/gf$ at stage 3 | 1/1 | 1/1.2 | 1/1.4 | 1/1.1 | 1/1.2 | 1/1.4 |
| Prob(%) | 42 | 21 | 7 | 18 | 9 | 3 |

Tables 1–3 present the construction data of feeders, substations, and VSCs for the planning system. The amount the DG connected to the DC system is given in Tables 4. As can be observed, VSCs and substations account for the main part of the investment costs, among which VSCs holds the largest proportion. Despite the large investment costs of VSC, the production costs can be significantly reduced by accommodating more renewable energy resources in the DC system.
Table 7 presents the load and DG curtailment of the expected planning solution under the other uncertain scenarios. As can be noted, when the growth of load demand and DG capacity exceed their predicted values, limited by the capacity of VSCs and substations, large-scale of DG and load curtailment will occur in the last two stages.

Then, the dynamic investment strategy without the limitation on disposable RFs is adopted among the uncertain scenarios, and the planning solutions are adjusted according to the related scenario information. Since the growth of load and DG exceed the predicted values, more equipment is constructed. For comparison, the adjusted planning solution under S5 is shown in case 2 of Fig. 6. As can be observed, there exists a significant difference in the last two stages between Case 1 and Case 2. In Case 2, substations, VSCs, and feeders with larger capacity are installed, which guarantees the power supply of load demand and the full accommodation of DG.

Fig. 7 illustrates the optimal investment costs under various uncertain scenarios. The blue bars represent the investment costs of stages 2 and 3, whereas the red curves indicate the increased proportions of the investment costs.
relative to the original plan. As can be observed, in S1-S3, as the installed DG capacities beyond expectations increase, additional investment costs required to optimize the planning solutions show an upward trend. Furthermore, the uncertainty of load demand and DG capacity are jointly considered in S4-S6, and higher additional investment costs are required. Since the construction costs of the substation and transformer are less than the VSC, S4 requires the least RFs among all the uncertain scenarios.

D. SENSITIVITY ANALYSIS ON THE RFs

When the disposable RFs are limited, the adjustment space of the plans is reduced, which has a significant influence on the optimal planning solutions. Thus, we perform a sensitivity analysis on the proportion of RFs. As can be observed from Fig. 7, the proportion of additional investment costs required in S6 is the highest, which is approximately 25%; thus, the disposable RFs proportion is set as 0%, 5%, 10%, 15%, 20%, and 25%, respectively.

The total costs and curtailment power of the optimal planning solutions with different proportions of RFs are presented in Fig. 8. The blue bars represent the total costs of the scheme, whereas the graphs represent the DG curtailment. As can be observed, when the proportion of disposable RFs increases, the total costs and DG curtailment of the scheme shows a downward trend under various uncertainty scenarios. The results reflect the value of RFs for improving the accommodation of DGs. It is worth noting that there is no load curtailment in each scenario. Since the penalty cost of load curtailment is relatively high, the investment costs are preferentially used to the substation installation to supply the load demand when adjusting the scheme.

In addition, as the disposable RFs increase, the total costs of the plans do not decrease linearly, and the decreasing trend slows down gradually, which indicates that the same disposable RFs correspond to different adjustment spaces of the planning solution. After the disposable RFs proportion exceeds the optimal value (corresponds to Fig. 7), the total costs of the scheme no longer decrease, and there is DG curtailment; thus, there is no adjustment space to reduce the total costs of the planning solution. Taking S2 as an example, when the disposable RFs proportion reaches 15%, the minimum total costs in this scenario has been achieved.

Fig. 9 illustrates the expected value of total costs under different scenarios with limited RFs proportions, where the data of scenario occurrence probability is obtained from Table 7. As can be observed, when the disposable RFs increases, the expected costs show a decreasing trend. The results reflect the flexible value of RFs to prevent investment risks under uncertainty. Furthermore, the decreasing trend of the expected values becomes slow as the proportion increases. With reference to Fig. 8, as the proportion increases from 0 to 5%, the total costs in S2 to S6 are all reduced, so the reduction of the expected value is relatively large. When the proportion increases from 20% to 25%, only the total costs in S5 and S6 decreases; in addition, the occurrence probability of these scenarios is low, so the reduction on the expected values is small. Therefore, reserving a high proportion of RFs may be a relatively conservative measure.
In summary, the numerical results of the testing system have demonstrated that the proposed planning approach can be used for long-term AC/DC hybrid DSEP problems under long-term uncertainty of load demand and DG, which reduce the total costs and promote the accommodation of DG. In addition, by solving the optimal planning solutions within different proportions of RFs, the flexible value of RFs and the investment risk can be adequately evaluated.

V. CONCLUSION

In this paper, a novel and flexible planning approach for the AC/DC hybrid distribution system is proposed, in which the flexible investment strategy is considered to address the development uncertainty of load demand and DG. The planning model aims to find the optimal multistage expansion plan, which includes the installation of substations, transformers, AC/DC feeders, VSCs, and SVGs. The planning decisions at each stage are adjusted sequentially as uncertain information revealed, and the additional investment costs are limited by the RFs. The overall problem is formulated as a MILP suitable for commercially available software.

Through a case study on an AC/DC hybrid system, we demonstrate that the proposed planning model can reduce the total costs and promote the accommodation of DG than the deterministic approaches under long-term development uncertainty. The flexible investment strategies hold significant value due to the ability to keep adjustment options in an uncertain environment, and the adjustment ability of the plans are significantly influenced by the RFs. Moreover, the sensitivity analysis on the proportion of RFs indicates that the investment risks of the planners are reduced with more disposable RFs, but reserving a high proportion of RFs may be too conservative, its proportion should be determined by the planners’ financial situation and perception of the uncertainty.

In future work, we plan to incorporate the demand response and energy storage systems to the planning model and analyze their effect on the planning solutions. Another area for improvement is the consideration of uncertainty at operating timescales related to volatile DG and load.

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