A Novel Receiving End Grid Planning Method with Mutually Exclusive Constraints in Alternating Current/Direct Current Lines

Yi Luo 1, Yin Zhang 1, Muyi Tang 1,*, Youbin Zhou 2, Ying Wang 2, Defu Cai 2 and Haiguang Liu 2

School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China; luoyee@hust.edu.cn (Y.L.); zhangyin9483@163.com (Y.Z.)

Electric Power Research Institute of Hubei Electric Power Company, Wuhan 430074, China; zhouybin@sohu.com (Y.Z.); angyin32@foxmail.com (Y.W.); defucai@foxmail.com (D.C.);
lhg071@126.com (H.L.)

* Correspondence: m201971388@hust.edu.cn

Abstract: The large-scale application of high-voltage direct current (HVDC) transmission technology introduces mutually exclusive constraints (MEC) into the power grid planning, which deepens the complexity of power grid planning. The MECs decrease the planning efficiency and effectiveness of the conventional method. This paper proposes a novel hybrid alternating current (AC)/direct current (DC) receiving end grid planning method with MECs in AC/DC lines. The constraint satisfaction problem (CSP) is utilized to model the MECs in candidate lines and then the detailed planning model, in which mutually exclusive candidate lines are described by mutually exclusive variable and constraint sets. Additionally, the proposed planning model takes the hybrid AC/DC power system stability into consideration by introducing the multi-infeed short circuit ratio (MISR). After establishing the hybrid AC/DC receiving end grid planning model with MECs, the backtracking search algorithm (BSA) is used to solve the optimal planning. The effectiveness of the proposed hybrid AC/DC grid planning method with MECs is verified by case studies.

Keywords: high-voltage direct current; high-voltage alternating current; mutually exclusive constraints; hybrid alternating current/direct current receiving end grid planning; multi-infeed short circuit ratio

1. Introduction

1.1. Motivation and Background

To solve the energy crisis, countries around the world are actively promoting renewable energy (RE) and increasing the proportion of RE in primary energy consumption [1–3]. However, most RE generation plants are remotely located and far away from the load centers due to the characteristics of their primary energy, which leads to the application of long-distance power transmission [4,5]. For example, the abundant RE in western China is transmitted to eastern China by long-distance transmission technologies; several long-distance transmission lines are going to be built in Europe to transmit the vast offshore wind power in the North Sea and Baltic Sea to continental Europe [6]. In long-distance transmission, the line commutated converter high-voltage direct current (LCC-HVDC) transmission technology has a dominant position due to its salient characteristics in economy and technology compared to the high-voltage alternating current (HVAC) transmission [7,8]. Though inferior to LCC-HVDC in economy and transmission capacity, the newly developed voltage source converters high-voltage direct current (VSC-HVDC) transmission technology has a good performance in dealing with the intermittency of RE [9,10]. As the key technologies to achieve an efficient integration and use of RE, the LCC-HVDC, VSC-HVDC, and AC/DC hybrid technologies have acquired a great importance worldwide.
Accordingly, hybrid AC/DC grid planning research has become a hot issue in power systems research.

In hybrid AC/DC grid planning, LCC-HVDC lines are dependent on their receiving AC grid because they require the receiving grid to have sufficient voltage support capacity. Otherwise, it may cause DC commutation failure [11]. Due to their high transmission power, the commutation failure may cause serious consequences [12]. Therefore, the AC/DC grid planning requires the collaborative optimization of AC and DC lines. The conventional stepwise planning method, which determines whether and how to build a DC line in the early stage and then plan an AC grid, needs to be improved.

In the AC/DC grid planning, some special mutually exclusive phenomena appear. For example, a DC converter station may have different candidate locations, which have different influences on the AC grid. However, one DC line can only have one drop point. The selection in multiple drop points constitutes a mutually exclusive problem. For another example, in the selection of construction lines’ type, DC lines can replace AC lines and m DC lines can replace at least n AC lines (m ≤ n) between two nodes. That is, whether to build DC lines or AC lines is also a mutually exclusive problem. In addition, the operation characteristics of DC lines and AC lines are quite different. The different operating characteristics of AC and DC lines, which have different impacts on the planning result, also have a feature of mutual exclusivity.

It can be seen from the above that the AC/DC grid planning is a coordinated optimization planning of AC and DC lines, and the mutual exclusivity in AC and DC lines needs to be considered.

1.2. Related Work

At present, the research on transmission grid planning with high proportion RE injection is relatively mature. Related studies are mainly focused on the following aspects:

1. multi-scenario-based stochastic transmission grid planning method [13,14];
2. probability-driven robust planning method [15];
3. coordinated planning method of network-generation considering multi-source complementarity [16,17];
4. transmission grid planning method coordinated with distribution network planning [18,19].

With the widespread application of HVDC transmission technology, the power systems present the complex characteristics of AC/DC hybrid technologies, and the planning research concerning hybrid AC/DC grids deserves attention. Considering the optimal power flow, reference [20] decomposes the optimal AC/DC grid planning into two nested problems, including the optimal AC/DC line configuration problem and the optimal power flow problem. In [21], a bi-level model is established to determine an optimal configuration of the hybrid AC/DC distribution system, where the upper level is the optimal configuration model of the hybrid distribution system and the lower level is established as a robust dispatch model to minimize the curtailment of RE when N-1 contingency happens.

Most hybrid AC/DC grid planning studies focus on distribution grids and microgrids. In these studies, the planning of the power grid is generally coupled with the planning of the generation due to the scale and integrity of the grid, which is quite different from the transmission grid. The planning study of the hybrid AC/DC transmission grid is still in the preliminary stage.

In [22], a hybrid AC/DC transmission grid expansion planning algorithm is presented for a system operator to choose the appropriate AC/DC lines, and the outages of the generation units and transmission lines are taken into account to ensure the safety of the system. In addition to a new AC/DC line, reference [23] puts the conversion plan of existing HVAC lines to HVDC lines into the planning scheme. Meanwhile, large-scale energy storage devices are planned to handle the intermittency of RE. Under the market environment, a market-based VSC-HVDC lines expanding approach, which connects different regional electricity markets, is proposed in [24]. As to the receiving end grid, reference [25] analyzes
the difficulties and risks of grid planning under multiple AC/DC lines feed-in, and a VSC-HVDC lines planning model is proposed to maximize the transmission section capacity. The above studies have carried out hybrid AC/DC transmission grid planning from the perspective of ensuring safety, handling intermittency of RE, and considering the market. However, the planning studies are limited. They have not fully considered the mutually exclusive constraints, with which the line type should be put into the planning process and the conventional methods are unable to get the optimal planning scheme.

This paper considers the mutually exclusive phenomena of AC/DC lines in hybrid AC/DC grid planning and proposes a hybrid AC/DC receiving end grid planning method considering MECs in AC/DC lines. The CSP in the field of artificial intelligence is applied to modify the general planning model and to deal with MECs. The model employs mutually exclusive variables (MEV) to represent the decision of the mutually exclusive candidate lines, which have their own constraint sets. Through the MEV sets, range sets, and constraint sets, the MECs are fully embodied in the planning model. The BSA is used to solve the model. Finally, case studies are set to verify the effectiveness of the proposed method.

The rest of the paper is organized as follows. The mutually exclusive problem in AC/DC grid planning and its mathematical description by CSP are shown in Section 2. The CSP planning model of the AC/DC receiving end grid considering MECs is established in Section 3. Sections 4 and 5 present the solution method and the case study. Section 6 is the discussion part. Finally, Section 7 concludes the paper.

2. The Mutually Exclusive Problem in AC/DC Grid Planning and Its Mathematical Description by CSP

2.1. The MEC and CSP

The mutually exclusive problem in AC/DC grid planning considered in this paper mainly refers to:

1) Between the two nodes, only one type of HVAC line, LCC-HVDC line, and VSC-HVDC line can be built. Between the two nodes, the selection of the newly added LCC-HVDC line, VSC-HVDC line, and HVAC line constitutes a mutually exclusive problem;

2) The different line types correspond to different operating characteristics, which also constitute mutually exclusive characteristics.

The mutually exclusive problem of AC/DC grid planning usually appears in the optimization model as a constraint, and so it is called MEC. As to the MECs in the selection of the DC converter station’s location, we do not consider them in this paper, because the decision of the DC converter station’s location should take multiple environmental and social factors into account, which will greatly increase the complexity of the planning model.

The mutually exclusive problem can be expressed as a CSP. CSPs are a popular topic in artificial intelligence and operations research. In the framework of CSP, the entities in problems are represented as a set of homogeneous sets with finite conditions on variables, which provides a common basis for analyzing and solving many seemingly different related issues.

CSP is defined as a triple < X, D, C >, where X is the set of variables, D is the set of each variable’s range, and C is the set of constraints. Each variable in X corresponds to a range in D, and each constraint in C is composed of a subset of X and an incompatible assignment set. The solution of an CSP is the assignment of all the variables in the X set from their domain, and this assignment satisfies all the constraints simultaneously [26].

2.2. The Description of the Mutually Exclusive Problem in AC/DC Grid Planning by CSP

The mutually exclusive problem in AC/DC grid planning can be described by MEV set X, range set D, and line’s constraint set C.
In AC/DC grid planning, one MEV is the construction type of the candidate lines, \( \alpha_i \). \( \alpha_i \) is an integer, and its range is \( \{1, 2, 3\} \). The different values of \( \alpha_i \) correspond to different line types, which is shown in (1).

\[
\alpha_i = \begin{cases} 
1 & \text{HVAC line} \\
2 & \text{LCC – HVDC line} \\
3 & \text{VSC – HVDC line}
\end{cases}
\tag{1}
\]

where \( K \) is the number of mutually exclusive lines. In addition to the type variable, the construction state variable \( \gamma_i \) is also the MEV of mutually exclusive lines, and its range is \( \{0, 1\} \). \( \gamma_i = 0 \) and \( \gamma_i = 1 \) respectively represent line \( i \) when it is not put into construction and when it is put into construction.

After defining the MEVs, the MEV set \( X_1 \) is shown in (2).

\[
X_1 = \{\{\gamma_1, \alpha_1\}, \{\gamma_2, \alpha_2\}, \ldots, \{\gamma_i, \alpha_i\}, \ldots\} \quad i = 1, 2, \ldots, K
\tag{2}
\]

The MEV range set is \( D_1 \), shown in (3).

\[
D_1 = \{\{d_{\alpha_1}, d_{\gamma_1}\}, \{d_{\alpha_2}, d_{\gamma_2}\}, \ldots, \{d_{\alpha_i}, d_{\gamma_i}\}, \ldots\} \quad i = 1, 2, \ldots, K
\tag{3}
\]

where \( d_{\alpha_i} \) is the range of construction type, and \( d_{\gamma_i} \) is the range of construction state variable. They satisfy (4) and (5):

\[
d_{\alpha_i} = \{1, 2, 3\}
\tag{4}
\]

\[
d_{\gamma_i} = \{0, 1\}
\tag{5}
\]

In AC/DC grid planning, the line’s constraint set \( C_1 \) is listed as follows (6).

\[
C_1 = \{\{\gamma_1, \alpha_1, S_1\}, \{\gamma_2, \alpha_2, S_2\}, \ldots, \{\gamma_i, \alpha_i, S_i\}, \ldots\}
\tag{6}
\]

where \( S_i \) is the line \( i \)'s constraint set. \( s_1, s_2, s_3 \) respectively refer to the planning and operating constraint sets of the HVAC lines, the LCC-HVDC lines, and the VSC-HVDC lines. \( S_i \) corresponds to the different constraint set when \( \alpha_i \) takes 1, 2, and 3, respectively.

In addition to the power flow constraints, constraints such as the DC converter station capacity constraint and the DC line operating constraint should be taken into account as well when applying the VSC-HVDC and LCC-HVDC transmission technologies. The detailed planning and operating constraint sets of different lines are shown below.

2.2.1. \( s_1 \), The Planning and Operating Constraint Set of HVAC Lines

Unlike the power flow analysis, the DC power flow model is sufficient to describe the operation state of AC lines in planning research. The planning and operating constraint set of HVAC lines are mainly the DC power flow model, as follows.

1. Branch power formula

In the DC power flow model, the branch power has a linear relationship with the node phase angle. The branch power formula is shown in (7).

\[
P_{L} = B_{l}(\theta_{s} - \theta_{r})
\tag{7}
\]

where \( P_{L} \) is the power flow of line \( l \). \( B_{l} \) is the susceptance of line \( l \). \( \theta_{s}, \theta_{r} \) represent the head nodes and the tail nodes of line \( l \)

2. Branch power flow limit constraint

Network security constraints should be considered in the planning model. The power flow of each line cannot exceed its capacity (8).

\[
-P_{L}^{\text{max}} \leq P_{L} \leq P_{L}^{\text{max}}
\tag{8}
\]
where $P_{l, \text{max}}$ is the capacity of line $l$.

3. **Node phase angle constraint**
   To ensure operation security, the node phase angle cannot exceed its range.
   \[ -\pi \leq \theta \leq \pi \]  \hfill (9)

The constraints (7)–(9) constitute the constraint set of HVAC lines.

### 2.2.2. $s_2$, the Planning and Operating Constraint Set of LCC-HVDC Lines

The operation mode of DC lines is quite different from that of AC lines [27]. The LCC-HVDC lines run in controlled mode, while the power flow of AC lines can be optimized freely within the capacity limit. The unique planning and operational constraints as to LCC-HVDC lines are listed as follows.

1. **DC line’s transmission power constraint**
   The DC line’s transmission power shall not exceed the maximum power limit or be lower than the minimum power limit. Otherwise, the DC line will fail and quit operation.
   \[ P_{DC}^i = 0 \cup P_{DC, \text{min}}^i \leq P_{DC}^i \leq P_{DC, \text{max}}^i \]  \hfill (10)
   where $P_{DC}^i$ is the transmission power of the DC line. $P_{DC, \text{min}}^i$, $P_{DC, \text{max}}^i$ represent the minimum and maximum power of the DC line.

2. **Converter stations capacity constraint**
   The power of DC converter stations should not exceed their capacity.
   \[ S_i \leq S_{i, \text{max}} \]  \hfill (11)
   where $S_i$, $S_{i, \text{max}}$ are the power and capacity of the converter station respectively.

3. **MISCR constraint**
   As an important index measuring the stability and security of power systems, the MISCR index is considered in the proposed planning model to ensure the feasibility of the planning results, and it should not be less than three in (12).
   \[ \text{MISCR}_i = \frac{S_{i, \text{Con}}}{P_{i, \text{DC, max}}} + \frac{\sum_{j=1, j\neq i}^n F_{j-i} P_{j, \text{DC, max}}}{P_{i, \text{DC, max}}} \geq 3 \]  \hfill (12)
   where MISCR$_i$ is the MISCR of DC line $i$. $S_{i, \text{Con}}$ is the short circuit capacity of the converter station’s bus. $F_{j-i}$ is the impact factor between line $i$ and $j$.

The constraints (10)–(12) constitute the constraint set of LCC-HVDC lines.

### 2.2.3. $s_3$, The Planning and Operating Constraint Set of VSC-HVDC Lines

In addition to the converter station capacity limit, the power flow direction change limit should be considered when selecting a VSC-HVDC line.

1. **Power flow direction change constraint**
   The frequent change of power flow direction is not allowed in the operation of VSC-HVDC lines, so the time interval of the direction change should be limited.
   \[ \left| P_{i}^{DC} + P_{i^r + i}^{DC} \right| = \left| P_{i}^{DC} \right| + \left| P_{i^r + i}^{DC} \right|, \quad 0 \leq i \leq T \]  \hfill (13)
   where $t'$ represents the time at which the power flow direction of the DC line changes. $T$ represents the minimum time interval of direction change.

The constraints (11) and (13) constitute the constraint set of VSC-HVDC lines.
3. CSP Planning Model of the AC/DC Receiving End Grid Considering Mecs

In this section, the CSP description of MECs is introduced into the general planning model, and the CSP planning model of the AC/DC receiving end grid considering the MECs, including the objective function, the CSP description of candidate lines, and the general grid planning technical constraints, is as specified in the following explanations.

3.1. Objective Function

The objective of the planning problem is formulated in (14) to minimize investment and operation costs in both AC and DC systems. The operation cost mainly includes the maintenance cost, network loss cost, and network congestion cost.

\[
\min F_{IV} + F_{M} + F_{LO} + F_{RG} \tag{14}
\]

where \( F_{IV} \) is the investment cost of construction lines. \( F_{M} \), \( F_{LO} \), \( F_{RG} \) respectively describe the maintenance cost, the network loss cost, and the network congestion cost.

3.1.1. Investment Cost

In power grid planning, the investment cost is mainly the investment cost of transmission lines. It is the construction cost multiplied by the capital recovery rate (15):

\[
F_{IV} = \left( \sum_{i=1}^{N} C_i Z_i L_i \right) \cdot \frac{r(1+r)^{LT}}{(1+r)^{LT} - 1} \tag{15}
\]

where \( r \) is the annual interest rate. \( LT \) is the lifetime of the construction line. \( N \) is the number of candidate lines. \( C_i \) is the unit investment cost of new lines. \( L_i \) is the line length. What needs to be emphasized here is that the transmission capacities of the candidate lines are determined in advance according to the construction type, and they are not optimized in this model.

3.1.2. Maintenance Cost

It is necessary to regularly maintain the grid or take emergency measures in case of failure. The maintenance cost is proportional to the new lines' investment cost, not including the existing line. The maintenance cost is described as (16):

\[
F_{M} = \sum_{i=1}^{N} \varepsilon_i C_i Z_i L_i \tag{16}
\]

where \( \varepsilon_i \) represents the maintenance cost ratio.

3.1.3. Network Loss Cost

The network loss is a significant factor in grid planning. To decrease network loss, the network loss cost is added to the objective function. Since it is difficult to calculate the total network loss, the maximum network loss is introduced for simplicity. The network loss cost is determined as follows:

\[
F_{LO} = C_{LOSS} \cdot E_{LOSS} \tag{17}
\]

\[
E_{LOSS} = T_{max} \cdot \max_{i \in N_{L}} \left\{ \sum_{i=1}^{N_{L, All}} \left( Z_i \cdot r_i \cdot (P_{i,j}^L / U_{i,j})^2 \right) \right\} \tag{18}
\]

where \( C_{LOSS} \) represents the network loss cost factor. \( E_{LOSS} \) indicates the total network loss power. \( T_{max} \) is the maximum network loss duration time. \( P_{i,j}^L \) is the power of line \( i \) at maximum network loss moment. \( N_{L, All} \) is the operation line set. \( U_{i,j} \) is the voltage of the node connected to line \( i \). \( r_i \) is the resistance of the line.
3.1.4. Network Congestion Cost

When network congestion happens, the RE in some nodes may be unable to put into the network and may be curtailed. In order to keep balance, the power transfer exists in different energy suppliers, leading inevitably to operational cost change. Equations (19)–(23) are the description of network congestion cost.

\[
F_{RG} = f_{RG} + f_{RW} + f_{RH}
\]

\[
f_{RG} = T_{RG} \cdot C_{G-G} \cdot \sum_{i=1}^{N_G} (p_{i,t,0}^G - p_{i,t,1}^G)
\]

\[
\sum_{i=1}^{N_G} (p_{i,t,0}^G - p_{i,t,1}^G) = 0
\]

\[
f_{RW} = C_G \cdot T_{RG} \cdot \sum_{i=1}^{N_W} \Delta P_{i,t,1}^W
\]

\[
f_{RH} = C_G \cdot T_{RG} \cdot \sum_{i=1}^{N_H} \Delta P_{i,t,1}^H
\]

where \(f_{RG}, f_{RW}, f_{RH}\) respectively describe the congestion cost of the thermal unit, the wind farm, and the hydropower station. \(N_G, N_W, N_H\) are the set of the thermal unit, the wind farm, and the hydropower station, respectively. \(T_{RG}\) is the maximum congestion duration time. \(C_{G-G}\) is the internal power transfer cost of the thermal unit. \(C_G\) is the power transfer cost of the wind power and hydropower to the thermal unit. \(t_1\) is the maximum network congestion moment. \(p_{i,t,0}^G, p_{i,t,1}^G\) stand for the scheduled and actual thermal power in case of congestion. \(\Delta P_{i,t,1}^W, \Delta P_{i,t,1}^H\) are the power transfer of wind power and hydropower.

3.2. The CSP Description of Candidate Lines

The constraints of the planning problem contain two parts:

1. the CSP description of all candidate lines, with the lines variable set \(X\), range set \(D\), and line’s constraint set \(C\) included;
2. general technical constraints of the AC/DC grid planning.

Based on Section 2.2, this section talks about the CSP description of all candidate lines, and the next section indicates the general constraints of the AC/DC grid planning.

The variables, the variable ranges, and the constraint set of all candidate lines can be described as follows ((24)–(26), in which both the mutually exclusive candidate lines and the normal candidate lines are described).

\[
X = \{\{\gamma_1, a_1\}, \{\gamma_2, a_2\}, \ldots, \{\gamma_i, a_i\}, \ldots, \{\gamma_K, a_K\}, \ldots, \{\gamma_N, a_N\}\}
\]

\[
D = \{\{d_{\gamma_1}, d_{a_1}\}, \{d_{\gamma_2}, d_{a_2}\}, \ldots, \{d_{\gamma_i}, d_{a_i}\}, \ldots, \{d_{\gamma_K}, d_{a_K}\}, \ldots, \{d_{\gamma_N}, d_{a_N}\}\}
\]

\[
C = \{\{\gamma_1, a_1, S_1\}, \{\gamma_2, a_2, S_2\}, \ldots, \{\gamma_i, a_i, S_i\}, \ldots, \{\gamma_K, a_K, S_K\}, \ldots, \{\gamma_N, a_N, S_N\}\}
\]

In the variable set \(X\) and the variable range set \(D\), the first \(K\) subsets refer to candidate lines with MECs. The \(\gamma_i\) and the \(a_i\) are all variables, and each can choose any value in its range set, which means that the mutual exclusivity exists in the planning process.
The other N-K candidate lines do not have MECs, and for each line \( i \) only the construction state variable is the decision variable, while the construction state variable is certain in the planning model, which is determined in advance in reality. As shown in the range set \( D \), the range of the construction state variable of the other N-K is merely one value. What needs to be emphasized is that in the constraint set \( C \), the \( j \) is indeed not a variable and it is certain for each \( i \) from \( K + 1 \) to \( N \).

### 3.3. General AC/DC Grid Planning Technical Constraints B

These constraints must be followed for grid planning, and have nothing to do with the construction type of the line. The general constraints considered in this paper are listed as follows.

1. **Line’s construction time constraint**

   According to the construction plan of generation plants and substations, certain lines have restrictions on commissioning stages in the planning scheme. The constraint is shown in (27), which restricts the lines’ construction time.

   \[
   \gamma_i = \begin{cases} 
   0 & t < t_{i,\text{min}} \\
   1 & t \geq t_{i,\text{max}} 
   \end{cases} \tag{27}
   \]

   where \( t_{i,\text{min}}, t_{i,\text{max}} \) respectively represent the earliest and latest construction time of line \( i \).

2. **Line’s construction sequence constraint**

   In reality, line \( i \) must be constructed before line \( j \), and restrictions are given on the construction sequence of some AC/DC lines.

   \[
   \gamma_i \geq \gamma_j \quad \forall t \tag{28}
   \]

3. **The power balance constraint**

   In operation, the power systems must keep the power balance. The power injected in the node is equal to the power flowing out.

   \[
   \sum_{i,g} \alpha_n p^g_i - p^D_n + p^n_{\text{D,curtail}} = \sum_i p^\text{L,in}_i - \sum_i p^\text{L,out}_i \tag{29}
   \]

   where \( \alpha_n \) is the generator set connected to node \( n \). \( \varphi_n, \rho_n \) represent the line sets flow in and out node \( n \), and the line sets contain not only the initial lines but also the planned lines. \( g \) is the generator type index, which includes thermal power, wind power, and hydropower. \( p^g_i \) is the output of generator \( i \) of type \( g \). \( p^\text{L,in}_i, p^\text{L,out}_i \) are the power of lines flowing in and out node \( n \), respectively. \( p^D_n, p^n_{\text{D,curtail}} \) are the load power and load curtailment of node \( n \), respectively. In (29), the branch power formula depends on the type of line.

4. **The unit output constraint**

   The output of each unit should be within its maximum and minimum limit.

   \[
   p^g_{i,\text{min}} \leq p^g_i \leq p^g_{i,\text{max}} \tag{30}
   \]

   where \( p^g_{i,\text{min}}, p^g_{i,\text{max}} \) stand for the minimum output and capacity of generator, respectively.

5. **The load supply constraint**

   To ensure the power supply quality, it is not allowed to curtail the load when the system operates normally or the N-1 contingency happens.

   \[
   p^\text{D,curtail}_n = 0 \tag{31}
   \]
4. Solution Technique

As to the CSP grid planning model, the BSA with independent pattern coding can solve it efficiently [28–30]. The characteristic of the BSA lies in using the deep search first algorithm to search the subtree, and its biggest advantage is that the subtree can use a constraint set to prune the constraint of a subtree without a solution. Additionally, the characteristics of mutually exclusive resource allocation and independence of the MECs have been completely proved. Therefore, the BSA is a potential method to solve the CSP planning model with MECs. The detailed process of the BSA in solving the CSP grid planning above is shown in Algorithm 1.

Algorithm 1: BSA for the CSP grid planning

1: Initialization, set initial value of candidate line set
2: Construct the solution tree based on candidate lines and node code, construct a virtual network
3: Calculate the power flow of the network
4: Calculate the economy and efficiency index of candidate lines
5: Cut the line with the smallest index
   If the result violates the safety index or the network is not disconnected
      Step 3
   Else
      Step 7
6: Bring back cut line
   If the feasibility check of the combination tree of candidate lines finished
      Step 3
   Else
      Step 9
7: Output the planning scheme

5. Case Study

The case study uses the 18-node test system in reference [31] and adds the DC line. The load data and generation data are listed in [31] as well. The system has 10 nodes and 9 lines, including 2 DC lines. In a future level year, the system will expand to 18 nodes, a total of 32 expandable lines. Node 10, 11, 14, and 16 have wind power access, and the capacities are 200, 200, 100, and 100 MW, respectively. The initial state of the system is shown in Figure 1, where the solid lines stand for the existing lines and the dotted lines are the candidate lines. The construction types of candidate lines contain HVAC lines, LCC-HVDC lines, and VSC-HVDC lines. If the candidate lines have MECs, they can be expanded in three different types. Otherwise, the construction type is determined in advance, and the construction type is not put into optimization.

Due to the uncertainty of wind power, the planning scheme needs to meet the safety constraint under multiple wind power output scenarios. This article assumes that the output characteristics of the four wind farms are the same and are all similar to a typical wind farm in western China. According to the wind power output and local maximum load date in the past two years, four typical scenarios of the continuous output of wind farms are obtained by the feature extraction and the cluster analysis of the K-means method, which are shown in Figure 2. The probabilities of scenarios 1–4 are 0.16, 0.44, 0.15, and 0.25, respectively. The maximum wind power (standard unit) in different scenarios is 0.58, 0.5, 0.8, 0.7 respectively. What needs to be emphasized here is that the method dealing with the uncertainty is a simplified method. The topic of this paper is not to deal with uncertainty, so this simplification is acceptable.
5.1. Planning Results with Different Mutually Exclusive Line Sets

When the mutually exclusive line sets are different, the complexity of grid planning varies to some extent. This section compares the results of the CSP grid planning model proposed in this paper with different mutually exclusive line sets. Two line sets containing different mutually exclusive lines are used to test the proposed CSP planning method, as shown in Case 1 and Case 2.

Case 1: In the candidate line set, one line from node 11 to 12, the line from node 7 to 9, the line from node 10 to 18, and the lines from node 4 to 16 have MECs. The proposed CSP planning method is used to select expanding lines.

Case 2: In the candidate line set, one line from node 11 to 12, one line from node 9 to 10, the line from node 7 to 9, the line from node 10 to 18, the line from node 1 to 11, and the lines from node 4 to 16 have MECs. The proposed planning method is used to select expanding lines.

The planning schemes of Case 1 and Case 2, obtained by the CSP planning method with different mutually exclusive line sets, are shown in Figures 3 and 4. The detailed parameter comparison of the planning results is shown in Tables 1 and 2.
Table 1. Comparison of the planning results with different MEC line sets.

| Comparison Item                        | Case 1                                                                 | Case 2                                                                 |
|----------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|
| Difference of the MEC Lines in Two Cases | One Lines 11–12, Lines 7–9, Lines 10–18, Lines 4–16                    | One Lines 11–12, One Lines 9–10, Lines 7–9, Lines 10–18, Lines 1–11, Lines 4–16 |
| Difference of the Expanded Lines       | 9–10HVAC × 2                                                            | 9–10LCC-HVDC                                                           |
| Number of New Lines                    | 20                                                                     | 19                                                                     |
| Expanded Lines Length/Km               | 2005                                                                   | 1830                                                                   |
| Whether to Optimize the DC Line        | YES                                                                    | YES                                                                    |
| Investment Cost (MCNY)                 | 2148.0                                                                 | 2125.0                                                                 |
Table 2. Planning results with different MEC line sets in different scenarios.

| Case | Scenario | Network Loss Rate | Wind Power Curtailment Rate | MISCR (Node 6/12/9) | Maximum Load Rate |
|------|----------|-------------------|-----------------------------|----------------------|------------------|
|      |          |                   |                             |                      |                  |
| Case 1 | 1        | 2.24%             | 4.37%                       | 3.36/3.77/—–        | 77.23%           |
|       | 2        | 2.43%             | 3.45%                       | 3.36/3.77/—–        | 83.30%           |
|       | 3        | 2.17%             | 6.28%                       | 3.36/3.77/—–        | 71.83%           |
|       | 4        | 2.50%             | 6.73%                       | 3.36/3.77/—–        | 69.42%           |
| Case 2 | 1        | 2.12%             | 3.94%                       | 3.36/3.77/3.45      | 77.23%           |
|       | 2        | 2.39%             | 3.39%                       | 3.36/3.77/3.45      | 83.30%           |
|       | 3        | 1.93%             | 5.68%                       | 3.36/3.77/3.45      | 71.83%           |
|       | 4        | 2.35%             | 5.82%                       | 3.36/3.77/3.45      | 69.42%           |

From the figures, though the MECs line sets are different, the right-hand networks of the two cases are still the same. This indicates that when the MEC line set changes, the planning result is relatively stable.

However, this does make a difference. In Case 1, 20 new lines will be built, including a VSC-HVDC line from node 11 to 12. The total length is about 2005 km. The planning scheme of Case 2 will construct 19 new lines, with a VSC-HVDC line from node 11 to 12 and an LCC-HVDC line from node 9 to 10 included, and the total length is 1830 km. The red box in Figure 4 indicates its difference with Figure 3.

Due to the existence of MECs in lines from node 9 to 10, one LCC-HVDC line with a larger transmission capacity is chosen in Case 2 after optimization. While in Case 1, two HVAC lines are planned because there is no MECs in lines from node 9 to 10. The application of the LCC-HVDC line from node 9 to 10 in Case 2 enhances the transmission capacity and increases the wind power absorption capacity of node 10. Therefore, compared with Case 1, Case 2 has a lower network loss rate and a lower power abandonment rate, shown in Tables 1 and 2. Additionally, this LCC-HVDC line avoids the frequent direction change of the power flow in the 9-10-18-17-16-9 ring network when the operation mode changes. The power flow direction is 10-9 when the operation mode changes.

With the analysis above and the data in Table 1, it can be found that the parameter indexes of Case 1 and Case 2 are within a reasonable range. However, compared with Case 1, the planning result in Case 2 is better, because there are more MEC lines in Case 2 and more lines can be optimized.

5.2. Comparison with the Conventional Stepwise Expansion Method

At present, the common method in the planning of AC/DC grid is the stepwise expansion method. Its main idea is to plan other AC lines based on the determined DC lines, in which DC lines are not put into optimization. This section compares the AC/DC grid planning method presented in this paper with the stepwise expansion method by numerical analysis. The stepwise expansion method is applied to plan the 18-node test system, as shown in Case 3.

Case 3: In the stepwise expansion method, it is artificially determined in advance that one VSC-HVDC line will be built from node 11–12, and one LCC-HVDC line will be built from node 9–10. Other AC lines are planned freely.

The planning scheme of Case 3 is shown in Figure 5. A total of 19 new lines will be built, with a total length of about 1810 km. Tables 3 and 4 compare the detailed planning results of Case 2 and Case 3.
Table 3. Comparison of the method proposed and the stepwise expansion method.

| Comparison Item                              | Case 3                                      | Case 2                                      |
|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| Difference of the MEC Lines in Two Cases    | No MEC                                      | One Lines 11–12, One Lines 9–10, Lines 7–9, |
|                                             |                                             | Lines 10–18, Lines 1–11, Lines 4–16         |
| Difference of the Expanded Lines            | 6–13HVAC                                    | 12–13HVAC                                  |
| Number of New Lines                         | 19                                          | 19                                          |
| Expanded Lines Length (Km)                  | 1810                                        | 1830                                        |
| Whether to Optimize the DC Line             | No                                          | YES                                         |
| Investment Cost (MCNY)                      | 2077.0                                      | 2125.0                                      |

Table 4. Planning results of the method proposed and the stepwise expansion method in different scenarios.

| Case | Scenario | Network Loss Rate | Wind Power Curtailment Rate | MISCR (Node 6/12/9) | Maximum Load Rate |
|------|----------|-------------------|-----------------------------|----------------------|-------------------|
| Case 3 | | | | | |
| 1    | 2.10%    | 5.35%             | 3.36/1.87/3.45              | 83.21%               |
| 2    | 2.37%    | 6.76%             | 3.36/1.87/3.45              | 85.32%               |
| 3    | 1.73%    | 8.23%             | 3.36/1.87/3.45              | 79.25%               |
| 4    | 2.23%    | 7.49%             | 3.36/1.87/3.45              | 74.80%               |
| 1    | 2.12%    | 3.94%             | 3.36/3.77/3.45              | 77.23%               |
| 2    | 2.39%    | 3.39%             | 3.36/3.77/3.45              | 83.30%               |
| 3    | 1.93%    | 5.68%             | 3.36/3.77/3.45              | 71.83%               |
| 4    | 2.35%    | 5.82%             | 3.36/3.77/3.45              | 69.42%               |

As can be observed in the comparison, Case 2 optimizes the DC line. However, the stepwise expansion method used in Case 3 does not optimize the DC line, as it is unable to consider the supporting role of the AC grid in the LCC-HVDC line. The MISCR of node 12, which is the drop point of a planned LCC-HVDC line, is merely 1.87. It does not meet the voltage stability requirements and is not conducive to the stability of power systems. Additionally, the AC grid between node 5 and node 12 is a relatively independent isolated grid. This will affect the operation safety, because in the isolated grid, a power outage of the whole local power grid will happen when line 5–12 fails.

As to the wind power consumption, one transmission channel (node 12–13) of wind power at node 11 is reduced in Case 3, which leads to a great increase of the wind power curtailment rate compared to Case 2. Although there is no advantage in cost, Case 2
has obvious advantages over Case 3 in terms of power grid security and wind power consumption. This disadvantage in cost is mainly due to the fact that Case 2 is an optimal planning of the global hybrid AC/DC grid, while Case 3 is merely an optimal planning of the AC grid and it sacrifices the security of the hybrid AC/DC grid. It is suggested that a better planning result can be obtained by adding the selection of DC lines into the optimization process, which is the advantage of the proposed method compared with the conventional method.

5.3. Influence of the Wind Power Capacity Change on the Planning Scheme

To study the impact of wind power capacity on the planning scheme, based on Case 2, we consider the capacity of the wind farm connected to node 11 as 100 MW, 150 MW, 200 MW, 250 MW, and 300 MW, respectively. The comparison of the planning results is shown in Table 5.

Table 5. Comparison of the planning results with different wind farm capacity in node 11.

| Comparison Item                  | 100 MW       | 150 MW       | 200 MW       | 250 MW       | 300 MW       |
|----------------------------------|--------------|--------------|--------------|--------------|--------------|
| Difference of the Expanded Lines | node 11–12 HVAC | node 11–12 HVAC | node 11–12 VSC-HVDC | node 11–12 LCC-HVDC | node 11–12 LCC-HVDCDC |
| Number of New Lines              | 19           | 19           | 19           | 19           | 20           |
| Expanded Lines Length (Km)       | 1830         | 1830         | 1830         | 1830         | 1975         |
| Investment Cost (MCNY)           | 2008.0       | 2008.0       | 2125.0       | 2125.0       | 2634.0       |

It can be seen from Table 5 that with the wind farms’ capacity increasing, the obvious change in the planning scheme concerns the lines near the wind farm integration points. This is mainly due to the increase transmission demand for wind power. Additionally, the line investment costs of the grid planning results also increase accordingly.

Due to the large transmission ability of HVDC lines, the application of HVDC lines is more technologically conducive when the capacity of wind farms connected to node 11 exceeds 200 MW. Although the unit price of HVDC lines may be higher than that of the HVAC lines, it is better in terms of overall economic benefits. In this example, when the wind farm capacity is greater than or equal to 200 MW, the planning plan selects HVDC lines between node 11 and 12; when the capacity is less than 200 MW, the planning plan adds HVAC lines.

6. Discussion

Due to the importance of the receiving end grid in supplying loads and the simplicity of the traditional sending end grid, the AC/DC grid planning in this article is to study the receiving end grid. At present, the connection within the wind farm cluster at the sending end and the bundling of wind power, solar power, and thermal power have made the sending-end grid increasingly complicated, and the planning of the sending end AC/DC grid has gradually received attention. The method proposed in this paper also has a certain applicability to the sending-end grid planning, and the short-circuit ratio can still measure the stability of the power grid. However, because of the richness and complexity of RE at the sending end, the simulation of the volatility of multiple RE sources should be focused and the modeling of the complementarity of different energy sources needs to be considered.

The AC/DC grid planning described in this paper is carried out under the assumption that the government is responsible for the unified operation of the grid. When multiple investment and construction operators are involved, the grid planning should take competition among multiple investment entities into account, and the method described in this paper is no longer used. But when it comes to planning, the government-led mode
is actually more beneficial to the social welfare and security of the grid compared to the multi-operators mode.

7. Conclusions

The integration of large-scale RE introduces a widespread application of HVDC lines into the AC grid. The planning of the complex hybrid AC/DC grid faces big challenges, and the MECs in grid planning exacerbate the difficulty. In this paper, an optimal planning method for the AC/DC receiving end grid with MECs in candidate lines is proposed. The CSP theory is used to describe a hybrid AC/DC grid planning model and the MECs in the candidate lines, where MECs in the candidate lines are described by an MEV set, a range set, and a constraint set. Then, the BSA is used to solve the planning model. Through case studies, the feasibility of the proposed approach has been verified with major conclusions, as follows.

(1) The proposed model outperforms the conventional planning method in wind power consumption and network safety because it takes the selection of the line’s type into optimization and then successfully solves the problem of MECs. Additionally, the proposed model can get stable and reasonable expanding plans when the MEC line sets change. Thus the planning method modeled by CSP can effectively handle the planning issues of a hybrid AC/DC grid with MECs.

(2) The proposed model introduces a key index, the MISCR, into the hybrid AC/DC grid planning, by which the AC grid can be optimized to meet the voltage support demand of the DC lines. The obtained scheme performs better in terms of the stability of the power systems than the conventional method. The introduction of MISCR shows the adaptive change in this paper from the traditional AC grid planning to the hybrid AC/DC grid planning.

This paper only considers the MECs of AC and DC lines. Further research can take the MECs of the different DC converter station locations into account. Due to the large integration capacity of RE and its intermittency problem, it is of great significance to consider the multiple uncertainties and the coupling relationships within them in planning models.

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