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# A grid integration planning approach for partitioned super-large offshore wind farms considering onshore grid accommodation capacity

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Large-scale offshore wind energy development is crucial for energy transition. At present, there is no consideration of onshore grid accommodation capacity when integrating and planning offshore wind farm systems, which severely constrains the deployment of giga-scale projects, i.e., super-large offshore wind farms (SLOWFs). To achieve rational accommodation of wind power, we propose a transmission system planning method for partitioned SLOWFs by considering the accommodation capacity of the onshore power grid. First, based on the constraints of the onshore partition grid's accommodation capacity, we apply the density peak clustering algorithm to partition the SLOWF. Second, a double-layer planning model is established for the transmission system of the partitioned SLOWF; here, the upper-layer model focuses on layout optimizing of the offshore converter stations based on the partitioned SLOWF, while the lower-layer model addresses the planning of DC submarine cables and onshore converter stations. The overall economic optimization of the system is achieved by iteratively solving the double-layer model. Finally, the simulations are validated using the links of a SLOWF integrated with an actual coastal grid. The results demonstrate that the proposed model and solution method significantly reduce planning costs while improving the efficiency of convergence.

KEYWORDS

**super-large offshore wind farm, transmission system planning, converter station location and type, collaborative planning, density peak clustering algorithm, partition**

## 1 Introduction

The development of super-large offshore wind farms (SLOWFs) is an emerging trend in offshore wind energy generation. China has beneficial conditions for the construction and development of offshore wind power farms owing to its long coastline and vast sea area (Ye et al., 2019). The China National Development and Reform Commission has indicated plans to establish five 10-million-kilowatt-class SLOWFs during the 14th five-year plan period; these are expected to be located in the

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Shandong Peninsula, Yangtze River Delta, Southern Fujian, Eastern Guangdong, and Beibu Gulf. Large-scale SLOWFs will require access to coastal load centers even as coastal areas have limited accommodation capacities for such efforts. In addition, equipment planning can affect these efforts given the need for offshore converter stations, direct current (DC) submarine cables, and onshore converter stations, among others. Therefore, it is necessary to consider the capacities of onshore partitioned power grids for accommodating wind power and conducting transmission system planning for partitioned SLOWFs to achieve coordinated planning of each equipment in the transmission system.

Current studies on offshore wind power transmission system planning focus on small-scale offshore wind farms or wind farm clusters. The planning components include the locations and types of offshore substations or converter stations and onshore converter stations as well as types of transmission submarine cables. The substations reduce the high-voltage outputs from power plants to levels suitable for urban distribution networks or end-user consumption via transformers while also enabling power distribution, control, and fault protection. Converter stations convert alternating current (AC) into DC or *vice versa* using converters to facilitate interconnections between these types of power grids. To determine suitable locations for offshore substations and converter stations, some researchers have employed K-means clustering algorithm to group wind turbines (Huang et al., 2023; Cui et al., 2018). There are reports on applying the QT clustering method with the shortest distance as the clustering objective to group offshore wind farm clusters; the resulting cluster centers are then used as the locations for offshore substations (Xu et al., 2023). Some authors have utilized different heuristic optimization algorithms and combined them with clustering algorithms to iteratively optimize the number and locations of offshore substations (Peter et al., 2022; Huang and Huang, 2023; Zuo et al., 2021a; Eduardo et al., 2023). There are also reports on coordinated planning of offshore substations and transmission sea cables (He et al., 2024; Zuo et al., 2024; Zuo et al., 2021b). He et al. (2024) reported a planning model for grid integration of offshore wind farm clusters to optimize the types and locations of offshore substations as well as types and routing methods for sea cables. A double-layer planning model was proposed to collaboratively plan the topology of the collection system and transmission sea cables for offshore wind farms (Zuo et al., 2024; Zuo et al., 2021a). Some of the above works determined the locations and types of substations based on the premise that the number of substations is known (Huang et al., 2023; Cui et al., 2018; Xu et al., 2023). In such cases, the locations and types of substations are predefined, which limits the possibility of coordinated planning with transmission cables. Although some studies reported the planning of transmission topology (He et al., 2024; Zuo et al., 2024; Zuo et al., 2021b), they overlook the coordinated planning of the landing point and onshore converter station design for offshore wind power transmission systems. Moreover, extant studies do not consider the capacities of onshore partitioned grids when accommodating offshore wind power. Considering that coastal partitioned grids are unable to accommodate tens of gigawatts of offshore wind power, it is essential to partition SLOWFs and transmit their power to distinct onshore partitioned grids for accommodation. Therefore, the existing planning methods for offshore wind power transmission systems are not applicable to SLOWFs.

To address this problem, we propose a transmission system planning method that considers the accommodation capacity of the onshore power grid for partitioned SLOWFs. Here, the SLOWF is first partitioned using the density peak clustering algorithm (DPCA) by considering the onshore partitioned grid's accommodation capacity as a constraint. Then, considering that the planning of offshore converter stations within each partition is interdependent on the planning of DC submarine cables, landing points, and onshore converter stations, we develop a double-layer planning model for the transmission system of partitioned SLOWFs. Next, the double-layer model is solved by combining the DPCA with automatically determining the number of clusters (DPADN) and segmented genetic algorithm (SGA). Finally, a real SLOWF is considered as a case study to validate the effectiveness of the proposed method.

## 2 Partitioning method for SLOWFs based on the accommodation capacities of onshore power grids

The capacity of an onshore partitioned grid to accommodate offshore wind power is often limited; hence, when the capacity of the offshore wind power connected to coastal areas exceeds the active power accommodation capacities of these areas, there may be serious wind curtailment. The accommodation capacity of a power system or grid is defined as the maximum installed capacity or maximum renewable energy generating power that can be accommodated by the system under constraints like reliable power supply, safety, stability, and economical operation for a certain installed conventional power supply and load level (State Grid Corporation of China, 2017). Therefore, the planning of transmission systems for SLOWFs must consider the accommodation capacities of onshore partitioned grids to offshore wind power. Partitioned SLOWFs will transmit their outputs to different onshore partitioned grids for accommodation. Based on this scheme, we propose a transmission planning method for partitioned SLOWFs. Specifically, different partitions of the SLOWFs are connected to different onshore partitioned grids. Here, the number of partitions is equal to the number of corresponding onshore partitioned grids. The capacity of each partition must not exceed the accommodation capacity of its corresponding onshore partitioned grid to offshore wind power. A schematic illustration of a partitioned SLOWF is shown in Figure 1 by taking a two-partition case as an example. Assuming that the accommodation capacities of the 220-kV coastal partitioned grid and 500-kV partitioned grid are $S_1$ and $S_2$, respectively, the SLOWF is divided into two corresponding partitions. Each partition is constrained by the wind power accommodation capacity of its corresponding onshore grid. In the schematic, Partition 1 and Partition 2 are connected to the two onshore partitioned grids, and the total capacity of the wind turbines in each partition must not exceed the accommodation capacity of the corresponding onshore grid. The accommodation capacities of the onshore partitioned grids

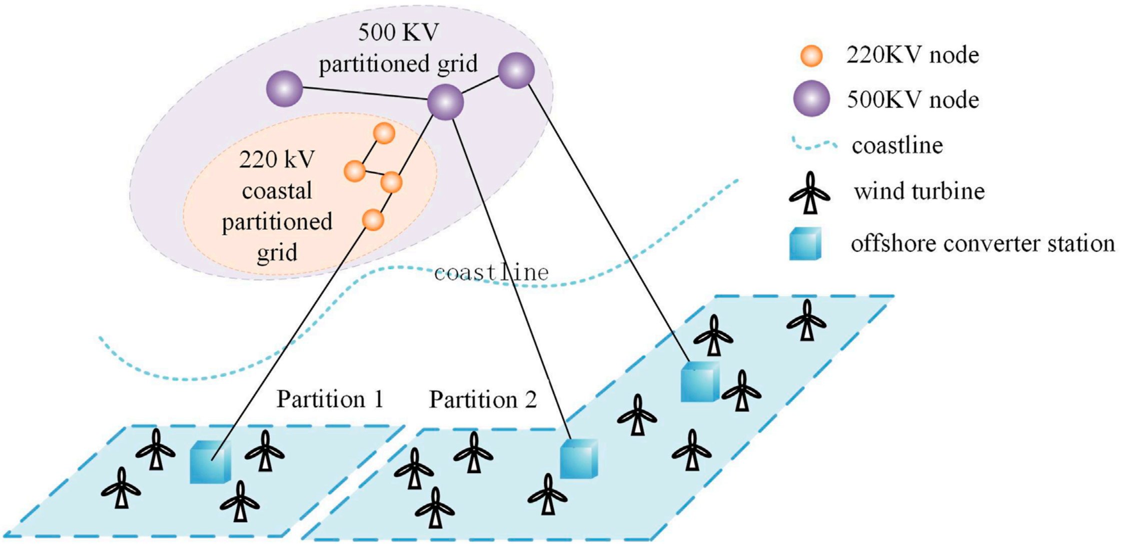


FIGURE 1
Diagram of a super-large offshore wind farm (SLOWF) with two partitions.

are calculated using the power balance equation reported by Liu et al. (2022).

Based on the partitioning concept, we propose a method for partitioned SLOWFs to determine the wind turbines assigned to each partition based on the accommodation capacity of its corresponding onshore partitioned grid. This involves determining the capacity of each partition as well as clustering and combining the wind turbines within each partition. The problem can be described as follows: given the coordinates and capacities of all the wind turbines in an SLOWF, the turbines are to be partitioned into $N^a$ different partitions such that the total capacity of the turbines in each of the partitions is constrained by the accommodation capacities of their corresponding onshore partitioned grids to offshore wind power. In this work, the wind turbines are partitioned using the DPCA. Unlike traditional distance-based clustering methods, the DPCA does not rely on a predetermined number of clusters. Instead, it identifies points with higher local densities and relatively large distances from other high-density points as the cluster centers. The DPCA is a clustering method based on density and distance without any built-in constraint mechanisms. Therefore, to address the partition capacity constraint, a constraint adjustment mechanism is incorporated into the clustering allocation process. Given the coordinates of each wind turbine as $(x_i, y_i)$ $(i \in 1, 2, \ldots)$ and the capacity constraint for partition $a$ as $S_a$, Figure 2 shows the flowchart of the partitioning method. The steps for solving the partitions are as follows:

1. Calculate the local density $\rho_i$. There are a total of $N_w$ turbines in the SLOWF, and the set of wind turbines can be denoted as $W = \{w_i\}_{i=1}^{N_w}$, with the local density of turbines $w_i$ defined as in Equation 1:

$$\rho_i = \sum_{j \neq i} \chi\left(d_{ij} - d_c\right), \tag{1}$$

where $d_{ij}$ is the Euclidean distance between two turbines $i$ and $j$; $d_c$ is the truncation distance. When $d_{ij} - d_c \geq 0$ , $\chi\left(d_{ij} - d_c\right) = 0$ ; otherwise, $\chi\left(d_{ij} - d_c\right) = 1$.

2. Calculate the relative distance to the high-density point $\delta_i$. For wind turbines with the highest local density, the relative distance is defined as the distance to the farthest wind turbine. For other wind turbines, the relative distance is the minimum distance from that turbine to all turbines with higher local densities. Thus, the relative distance of turbine $w_i$ is defined by Equation 2:

$$\delta_i = \begin{cases} \max\left(d_{ij}\right), \ \rho_i \text{ is maximum} \\ \min\left(d_{ij}\right), \ \rho_i < \rho_j \end{cases} \tag{2}$$

3. Select the $N^a$ points with higher densities and higher relative distances as the cluster centers, and assign the remaining points to the nearest neighboring clusters with high densities in descending order of density to obtain the initial partition scheme.
4. For each initial partition $a$, calculate the total capacity $S_a$ of its composite wind turbines and determine whether the partition capacity constraint is satisfied. If partition $a$ does not satisfy the constraint, then for all wind turbines $w_i$ inside $a$, calculate the minimum normalized distances $d_i$ to the centers of other partitions $\{P_b | b \neq a\}$ as shown in Equation 3:

$$d_i = \min_{b \neq a} \frac{d\left(w_i, P_b\right)}{\max_{w_j} d\left(w_j, P_b\right)} \tag{3}$$

Then, arrange the turbines in ascending order by $d_i$ and generate a pending queue $Q = \{w_1, w_2, \cdots, w_m\}$; now, sequentially reassign

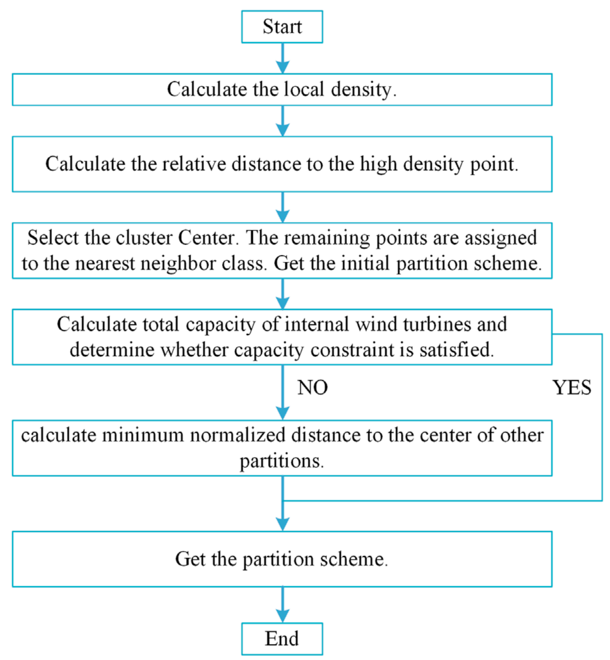


FIGURE 2
Partitioning method proposed in this work.

the turbines in $Q$ to their corresponding nearest non-overloaded partitions $b$, and update the partitions $a$ and $b$. If the reassignment of any turbine leads to overloading of its corresponding new partition $b$, pause the current assignment and prioritize the adjustment of partition $b$. Repeat the capacity check and partition adjustment steps until all partitions satisfy the capacity constraints.

# 3 Double-layer transmission system planning model for partitioned SLOWFs

The planning optimization of the transmission system for partitioned SLOWFs involves planning of the offshore converter stations, DC transmission sea cables, onshore converter stations, and landing points. Researchers have demonstrated that a method directly connecting the transmission system at 66 kV to offshore converter stations is more economical (Cai et al., 2019). Therefore, we do not consider offshore substations and focus only on the planning of offshore converter stations. The planning problem encompasses many variables that can be disassembled into two subproblems: 1) planning of the offshore converter station; 2) planning of the voltage source converter for high-voltage DC (VSC-HVDC) and onshore converter station optimization. These two subproblems interact with each other and have a coupling relationship. Based on the connection between these problems, we consider a coordinated optimization scheme for the offshore converter station, offshore VSC-HVDC, and onshore converter station for each partition. Thus, the framework for the double-layer planning model of the transmission system for partitioned SLOWFs is shown in Figure 3. Here, the upper-layer model is for planning the offshore converter station based on the partitioned SLOWF, while the lower-layer model is the optimization planning for the VSC-HVDC and onshore converter station. The lower-layer model will feed the planning costs of the DC cables and onshore converter station back to the upper-layer model. The upper-layer model then adjusts the numbers, location, and types of offshore converter stations based on the feedback information while dynamically updating the objective function. Next, the upper-layer model transmits the locations and capacities of the offshore converter stations to the lower-layer model. Through this iterative updating of the double-layer planning model, the optimal planning scheme for the transmission system of each partition of the SLOWF is determined finally. Below, we introduce the double-layer optimization planning model and its solution.

## 3.1 Offshore converter station planning model for partitioned SLOWFs

### 3.1.1 Objective function

The upper-layer model considers the total cost of transmission planning for a partitioned SLOWF as the objective function, including the investment costs of the offshore converter stations in each of the partitioned areas of the offshore wind base as well as the investment cost of VSC-HVDC transmission, as given by Equation 4:

$$\min C_{\Sigma} = \sum_{a=1}^{N^a} \left( C^a_{\text{off-sub}} + C^a_{connect} \right), \tag{4}$$

where $N^a$ is the total number of partitions, $a$ is the index number for the partitions, $C^a_{\text{off-sub}}$ is the total investment cost of the offshore converter stations in partition $a$, and $C^a_{connect}$ is the total investment cost of the flexible transmission cables in the partition $a$. Among these, the total investment cost of the offshore converter stations required for the offshore wind turbines is given by Equation 5:

$$C^a_{\text{off-sub}} = \sum_{\substack{h=1 \\ h\in\Lambda_{os}}}^{H} x_{h,os} n_{h,os} c_{h,os}, \tag{5}$$

where $h$ and $H$ are the capacity index and number of offshore converter stations, respectively; $\Lambda_{os}$ is the candidate set of existing models of offshore converter stations to ensure standardization of equipment selection, where each model corresponds to a different voltage level and capacity; $x_{h,os}$ is the 0–1 decision variable corresponding to the offshore converter station of type $h$, where 1 denotes that the station will be put into construction and 0 means otherwise; $n_{h,os}$ is the number of offshore converter stations of type $h$ to be constructed; $c_{h,os}$ is the unit construction cost of an offshore converter station of type $h$.

### 3.1.2 Constraints

#### 3.1.2.1 Offshore converter station capacity constraints

Each offshore converter station must have sufficient capacity to receive the total power of all the turbines connected to it, and the total power of a single partition connected to a converter station must be less than or equal to 85%–90% of its capacity. Hence, the capacity of an offshore converter station should not be less than

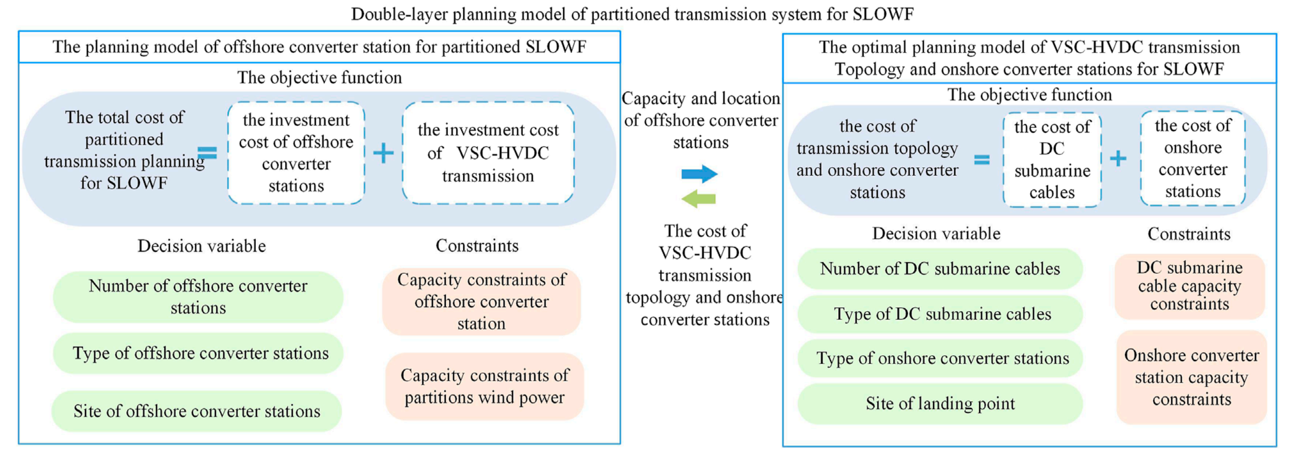


FIGURE 3
Framework of the double-layer planning model for partitioned SLOWFs.

the sum of the capacities of the wind turbines connected to it, as shown in Equation 6:

$$S^a_{h,os} \geq \sum_{w \in \Lambda_{ws}} S^a_w, \tag{6}$$

where $S^a_{h,os}$ is the capacity of the offshore converter station of type $h$; $\Lambda_{ws}$ is the set of offshore wind turbines connected to the offshore converter station; $S^a_w$ is the total capacity of the wind turbines $w$.

### 3.1.2.2 Capacity constraints of the partitioned SLOWF

The sum of the capacities of all offshore converter stations mapped to partition $a$ should not be less than the total capacity of the partition. Hence, the total capacity of all offshore converter stations mapped to a partition must be greater than or equal to 1.1–1.2 times of the total capacity of the partition, as given by Equation 7:

$$\sum_{os \in \Lambda_{a,OS}} S^a_{os} \geq S_a, \tag{7}$$

where $\Lambda_{a,OS}$ is the set of all offshore converter stations belonging to partition $a$; $S^a_{os}$ is the total capacity of the constructed offshore converter stations; $S_a$ is the total capacity of partition $a$.

## 3.2 Optimal planning model of VSC-HVDC transmission topology and onshore converter stations for SLOWFs

### 3.2.1 Objective function

The lower-layer model considers the total investment costs of the DC submarine cables and onshore converter stations as the objective function, as shown in Equation 8:

$$\min C^a_{connect} = C^a_{\text{cable}} + C^a_{\text{on-sub}}, \tag{8}$$

where $C^a_{\text{cable}}$ is the total investment cost of DC submarine cables required for offshore wind power transmission in partition $a$, as given by Equation 9, and $C^a_{\text{on-sub}}$ is the total investment cost of onshore converter stations required for offshore wind power transmission in partition $a$, as given by Equation 10:

$$C^a_{\text{cable}} = \sum_{n_{os}=1}^{N_{os}} \sum_{\substack{o=1 \\ o \in \Lambda_o}}^{N_o} \sum_{\substack{g=1 \\ g \in \Lambda_{cable}}}^{G} x_{g,o,n_{os}} n_{g,o,n_{os}} l_{g,o,n_{os}} c_g \tag{9}$$

$$C^a_{\text{on-sub}} = \sum_{\substack{d=1 \\ d \in \Lambda_{ls}}}^{D} x_{d,ls} n_{d,ls} c_{d,ls} \tag{10}$$

Here, $\Lambda_{cable}$ is the candidate set of DC cable types corresponding to each rated voltage level and transmission capacity; $\Lambda_{ls}$ is the candidate set of onshore converter station types; $\Lambda_o$ is the set of alternative landing points; $N_{os}$ is the number of offshore converter stations; $N_o$ is the total number of alternative landing sites; $G$ and $g$ are the number of DC cable types and the type index, respectively; $D$ and $d$ are the number of onshore converter stations and the type index, respectively; $x_{g,o,n_{os}}$ is the 0–1 decision variable corresponding to the DC submarine cable type $g$ between the offshore converter station and onshore landing point $o$; $n_{g,o,n_{os}}$, $l_{g,o,n_{os}}$, and $c_g$ represent the number of circuits, length, and unit distance cost of the corresponding DC submarine cable, respectively; $x_{d,ls}$ is the 0–1 decision variable corresponding to the onshore converter station of type $d$; $n_{d,ls}$ and $c_{d,ls}$ are the number of corresponding onshore converter stations and unit construction cost, respectively.

### 3.2.2 Constraints

#### 3.2.2.1 DC submarine cable capacity constraints

The transmission capacity of the DC submarine cables for a connected offshore converter station must not be less than the capacity of the station, as given by Equation 11:

$$\sum_{n_{os} \in \Lambda_{os,c}} n_{g,o,n_{os}} S^a_{g,o,n_{os}} \geq S^a_{h,n_{os}} \tag{11}$$

where $\Lambda_{os,c}$ is the set of DC submarine cables connected to the offshore converter station $n_{os}$; $S^a_{g,o,n_{os}}$ is the total capacity of the selected DC submarine cable of type $g$; $S^a_{h,n_{os}}$ is the total capacity of the $n_{os}$ offshore converter station of type $h$.

#### 3.2.2.2 Onshore converter station capacity constraints

The total capacity of an onshore converter station must not be less than the capacity of the offshore converter station connected to it, as given by Equation 12:

$$S^a_{d,n_{ls}} \geq \sum_{n_{ls} \in \Lambda_{ls}} S^a_{h,n_{ls}} \quad (12)$$

where $\Lambda_{ls}$ is the set of offshore converter stations connected to the $n_{ls}$-th onshore converter station; $S^a_{d,n_{ls}}$ is the total capacity of the onshore converter station $n_{ls}$ of type $d$; $S^a_{h,n_{ls}}$ is the total capacity of the selected offshore converter station with capacity $h$ connected to the onshore converter station $n_{ls}$.

#### 3.2.2.3 Voltage class constraints

The voltage levels of the offshore converter stations, DC submarine cables, and onshore converter stations should be consistent within a given selection.

#### 3.2.2.4 Turbine location constraints

$$\begin{cases} x_{\min} \leq x_i \leq x_{\max} \\ y_{\min} \leq y_i \leq y_{\max} \end{cases} \quad (13)$$

As depicted in Equation 13, $x_{\min}$, $x_{\max}$, $y_{\min}$, and $y_{\max}$ are the minimum and maximum $x$-coordinate and $y$-coordinate values allowed for the wind turbine locations, respectively.

#### 3.2.2.5 Distance constraint between wind turbines

$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq L_{\min} \quad (14)$$

As shown in Equation 14, $L_{\min}$ is the minimum distance required between any two turbines $i$ and $j$. Generally, this distance should not be less than 2.5 times the maximum rotating diameter of the turbine wings.

## 3.3 Solution method

Considering the mixed-integer non-linear characteristics of a double-layer planning model for the power transmission system of a partitioned SLOWF, we propose a collaborative solution using the DPADN and SGA. The processes involved in implementing the solution are described below.

### 3.3.1 Initial parameter setting based on DPADN

To solve the dependency of the K-means algorithm on manually preset parameters, we adopted the DPADN approach in this study to determine the initial parameters for the number, capacities, and locations of the offshore converter stations (Tong, 2022). Meanwhile, the capacity constraints are established according to practical engineering requirements. The solution method is as follows:

1. The clustering samples are considered the turbines in each partition. The local density and relative distance of each turbine point in the partition are calculated using the DPCA, as described in Section 2. The turbine points are then ranked in descending order of the local densities as $\{\rho_1, \cdots \rho_i, \cdots \rho_{N_a}\}$. The values of the density variations are calculated as $\Delta\rho = \rho_i - \rho_{i+1}$, and their average value is $\overline{\Delta\rho}$.
2. The decision graph is constructed using the relative distance as the vertical coordinate and local density as the horizontal coordinate values to dynamically identify the cluster centers. If $\Delta\rho_M > 2\overline{\Delta\rho}$, the noise points are the data points to the left of $\rho_M$ in the decision diagram; otherwise, we consider that there are no noise points. In the case of existence of noise points, to avoid selecting the noise points as cluster centers, the algorithm selects the turbine points satisfying $\rho_i > \overline{\rho}$ and $\delta_i > \overline{\delta}$ as the cluster centers; otherwise, it selects the turbine points at $\delta_i > \overline{\delta}$ as the cluster centers.
3. For clusters with excess capacity, a splitting and rebalancing mechanism is introduced. This mechanism selects the suboptimal density peak points within the overloaded clusters as new centers and migrates the wind turbines along the edges according to the minimum distance principle until all turbine allocations satisfy the capacity constraints of the converter stations. The final cluster center coordinates, total cluster capacities, and number of output clusters correspond to the locations, capacities, and number of initial offshore converter stations, respectively.
4. As the last step, the DPADN method is first used to perform spatial clustering with engineering constraints on the core components (converter stations, DC cables, and landing points) of the offshore wind base partitioned grid-connection system, which decomposes the large-scale system into several independent subsystems with reduced computational complexity. Subsequently, an iterative SGA is adopted to solve the double-layer model, where the upper layer selects the optimal partitioning scheme to minimize the total transmission cost between subsystems and lower layer optimizes the component parameters within subsystems using the partitioning results from the upper layer as boundaries. Meanwhile, convergence is ensured through strategies like adaptively adjusting the crossover and mutation probabilities during the iterative process while retaining high-quality individuals. The iterations terminate when the change rate of the objective function between consecutive iterations meets the preset threshold.

### 3.3.2 Model solution

The solution to the double-layer planning model of the transmission system for partitioned SLOWFs is shown in Figure 4, and the steps are as follows:

1. Initial population generation: Based on the method described in Section 3.3.1, the number, capacities, and locations of the offshore converter stations are set as the core parameters for the initial population. Random perturbations are then applied to these core parameters, and the number of converter stations within a partition is randomly increased or decreased along with simultaneous adjustment of their capacities to meet the capacity constraints. Lastly, Gaussian noise is imposed on the coordinates of the converter stations.
2. Using initial clustering results as the input initial population: The SGA combined with the K-means algorithm is used

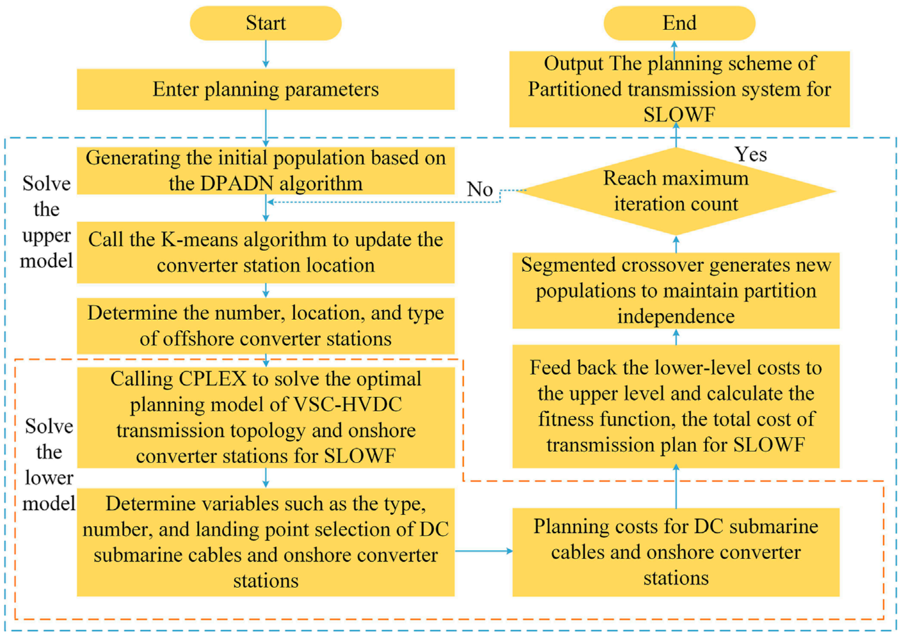


FIGURE 4
Solution process of the double-layer planning model for partitioned SLOWFs.

to correct the offshore converter station planning scheme. Among these, the SGA adopts a logical segmentation coding strategy to divide the chromosome into several subsegments equal to the number of partitions. Each subsegment contains the number, model, and location information of the offshore converter stations planned for the partition. When crossovers and mutations occur, the crossover point is a randomly selected partition boundary to maintain partition independence, and the corresponding subsegments of the parent generation are exchanged. Additionally, owing to the upper capacity limit of the offshore converter stations, we dynamically checked the capacity constraints of the offshore converter stations during K-means clustering to ensure that the upper limit is not exceeded. The K-means algorithm considering the capacity constraints is more reasonable for capacity allocation as the planning of the converter stations is more in line with practical engineering requirements.

3. Based on the converter station parameters determined by the upper-layer model, the lower-layer model employs the CPLEX solver to optimize variables like the capacities, quantities, and landing points of the DC submarine cables and onshore converter stations.
4. The objective function of the lower-layer model is fed back to the fitness function of the upper-layer model. Then, the genetic algorithm is used to optimize the decision variables like the number and capacities of the offshore converter stations. Finally, through continuous iteration, the planning scheme for the partitioned SLOWF is obtained based on the VSC-HVDC system.

To address the computational complexity and convergence issues caused by the large scale of the model, we first employed the DPADN approach to perform spatial clustering with engineering constraints on the converter stations, DC cables, and landing points of the transmission system for partitioned SLOWFs. This decomposes the large-scale system into several independent subsystems to reduce the computational complexity. Subsequently, the SGA is adopted to solve the double-layer model, where the upper layer selects the optimal partitioning scheme with the goal of minimizing the total transmission cost between subsystems and the lower layer optimizes the component parameters within these subsystems using the partitioning results from the upper layer as the boundaries. Meanwhile, convergence is ensured through the iterative process. The iterations are terminated when the change rate of the objective function between consecutive iterations meets the preset threshold.

## 4 Example analysis

To verify the effectiveness of the transmission planning method for partitioned SLOWFs proposed herein, we considered an actual SLOWF planned in the coastal area of China as the research object. This SLOWF contains 824 wind turbines whose coordinates are all known and has a total capacity of 9,984 MW. Further, there are seven candidate landing sites for this project.

### 4.1 Results of the partitioned SLOWF

Before solving the SLOWF transmission scheme, we first partitioned the SLOWF based on the accommodation capacity constraints of the onshore partitioned grid according to the method presented in Section 2. The accommodation capacities of the

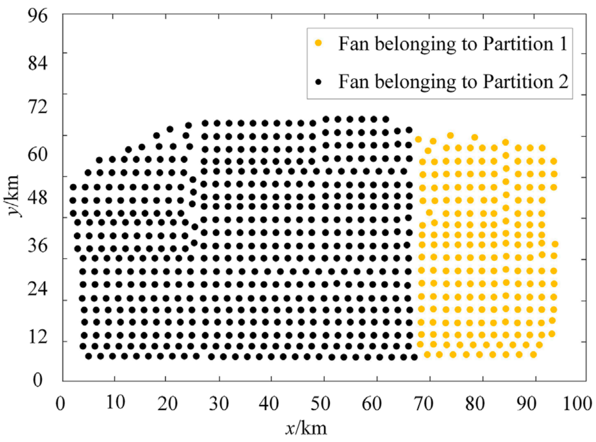


FIGURE 5
Layout of wind turbines located within the SLOWF partitions.

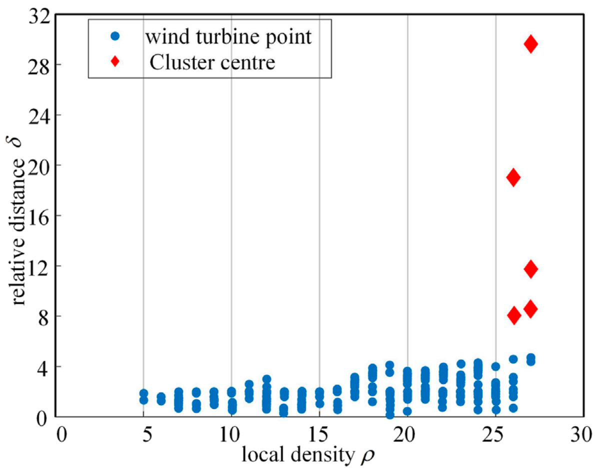


FIGURE 6
Decision diagram for clustering the wind turbines in Partition 2.

two onshore partitioned grids were known to be 2,500 MW and 7,780 MW, which are sufficient to accommodate the total installed capacity of the SLOWF. Therefore, the offshore wind base was divided into two partitions using the DPCA to group the wind turbines; Figure 5 shows the layout of the wind turbines after partitioning of the SLOWF. The total capacity of the turbines in Partition 1 (yellow dots) is 2,496 MW, and the total capacity of Partition 2 (black dots) is 7,392 MW; these partitions are planned to be sent to the two corresponding onshore partitioned power grids.

## 4.2 Scheme settings and comparative analysis

Based on the partitioned results, we verified the effectiveness of the double-layer planning model of the transmission system for the partitioned SLOWF by establishing three different schemes for comparative analysis.

Scheme 1: The offshore converter stations, VSC-HVDC system, and onshore converter stations are planned independently. Among these, the number, capacities, and locations of the offshore converter stations are obtained using the DPADN approach. The planning of the VSC-HVDC system and onshore converter stations is solved using the known locations, capacities, and other variables of the offshore converter stations. The planning results are then output for each variable.

Scheme 2: The equipment of the offshore converter stations of the SLOWF, VSC-HVDC system, and onshore converter stations are coordinated for planning. The segmented genetic algorithm is then used directly to solve the coordinated planning model, in which the number, capacities, and locations of the offshore converter stations are optimized by coding. The initial value of each variable is randomly generated.

Scheme 3: Based on the planning method proposed in this work, the solution method described in Section 3.3 is used.

### 4.2.1 Initial parameter settings

The Scheme 1 proposed above utilizes the DPADN approach to determine the initial parameters, namely the number of offshore converter stations as well as their capacities and locations. Thus, the initial parameters are set using the method described in Section 3.3.1. Briefly, a decision diagram is first generated according to the DPADN method; taking Partition 2 as the example, the decision diagram is shown in Figure 6. If there are no noise points in the decision diagram, the wind turbine points satisfying $\delta_i > \overline{\delta}$ are automatically selected as the clustering centers, and each wind turbine point is assigned in descending order of local density to the class where the closest high-density point is located. The red points in Figure 6 are the clustering centers (totaling five), and the clustering results for Partition 2 are shown in Figure 7. Next, the sum of all turbine capacities is calculated for each cluster, which resulted in five 1,500 MW offshore converter stations of 400 kV level each in Partition 2. Similarly, one offshore converter station of capacity 1,200 MW and one offshore converter station with a voltage rating of 400 kV for 1,500 MW capacity are planned in Partition 1. These results are used as the initial input parameters in Scheme 3. It should be noted that the initial parameters of Scheme 3 are the clustering results of the offshore converter station in Scheme 1 based on the settings discussed above.

### 4.2.2 Results

The above three schemes were calculated separately, and the number of iterations for Scheme 2, 3 were set equal to the number of populations per generation. The planning results of the three schemes are shown in Table 1. Figure 8 shows a schematic of the planning in Scheme 3. The locations of the offshore converter stations, onshore converter stations, and landing points as well as the relationships among the equipment planned in each scheme are marked in Figure 8. The landing points selected in Scheme 3 are the least in number. Thus, two partitions are formed offshore, where Partition 1 contains one and Partition 2 contains three offshore converter stations. Two of the offshore converter stations in Partition 2 are connected to the same onshore converter station. Hence, Partition 1 accesses one onshore converter station and Partition

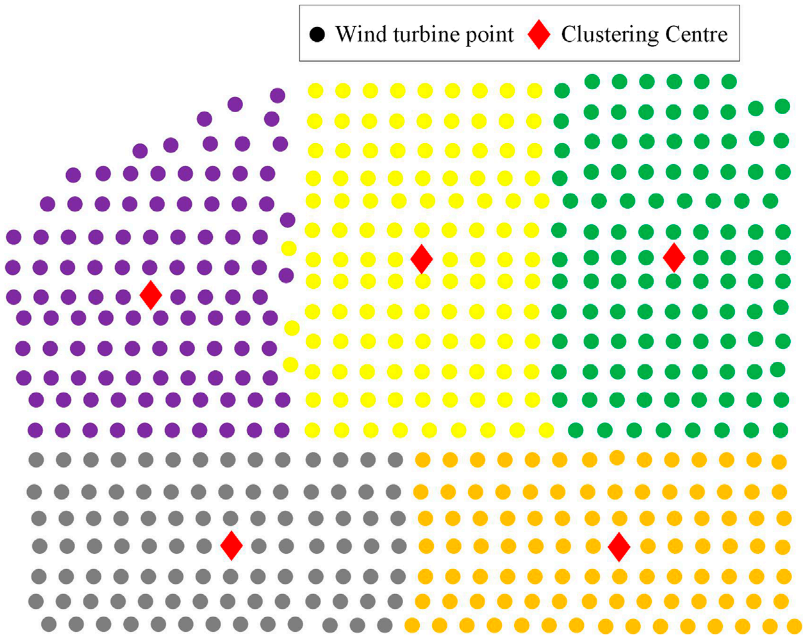


FIGURE 7
Initial clustering results for the wind turbines in Partition 2.

**TABLE 1 Planning results based on the different schemes.**

| Planning results | | Offshore converter stations | DC submarine cables | Onshore converter stations |
|---|---|---|---|---|
| Scheme 1 | Partition 1 | 1 × 1,200 MW + 1 × 1,500 MW (all 400 kV) | 1 × 1,200 MW + 2 × 900 MW (all 400 kV) | 2 × 1,500 MW (all 400 kV) |
| | Partition 2 | 5 × 1,500 MW (all 400 kV) | 10 × 900 MW (all 400 kV) | 5 × 1,500 MW (all 400 kV) |
| Scheme 2 | Partition 1 | 1 × 2,500 MW (500 kV) | 1 × 2,600 MW (500 kV) | 1 × 2,500 MW (500 kV) |
| | Partition 2 | 3 × 2,000 MW + 1 × 1,600 MW (all 500 kV) | 3 × 2,000 MW + 1 × 1,650 MW (all 500 kV) | 2 × 4,000 MW (all 500 kV) |
| Scheme 3 | Partition 1 | 1 × 2,500 MW (500 kV) | 1 × 2,600 MW (500 kV) | 1 × 2,500 MW (500 kV) |
| | Partition 2 | 3 × 2,500 MW (all 500 kV) | 3 × 2,600 MW (all 500 kV) | 1 × 2,500 MW + 1 × 5,000 MW (all 500 kV) |

2 accesses two onshore converter stations, whereby three landing points are selected finally.

### 4.2.3 Comparative analysis of results

Figure 9 shows the cost comparison results of the three schemes, where the proposed planning scheme exhibits optimal economic performance. The total cost of transmission planning for the partitioned SLOWF based on Scheme 3 reduced by 22.65% and 3.31% compared to the costs of Scheme 1 and Scheme 2, respectively. The reasons for this improvement may be analyzed as follows. Scheme 1 achieves direct offshore converter station planning via the DPADN approach. As shown in Table 1, the numbers of offshore converter stations planned in Partition 1 and Partition 2 based on Scheme 1 are higher than those obtained with the other schemes. This is because Scheme 1 selects offshore converter stations at the 400 kV level with small capacities to ensure the maximum number of clusters (number of equipment). Although small-capacity equipment have low unit costs, the quantity disadvantage results in high costs for offshore converter stations. Since the planning of DC submarine transmission cables is based on the results of the partitioned SLOWF, the DC submarine cables selected must also be of the 400 kV level type and capacity to meet the constraints to of the offshore converter station. Thus, the five offshore converter stations require 10 circuits each of the 400 kV DC submarine cables for power transmission, which corresponds to the construction of five onshore converter stations. Therefore, based on known variables like the offshore converter station locations, the cost of independent planning for the VSC-HVDC system is also maximum for Scheme 1. Consequently, Scheme 1 incurs the highest total cost for partitioned power transmission planning of the SLOWF.

Scheme 2 uses the SGA for coordinated equipment planning of the offshore converter stations with the SLOWF, VSC-HVDC system, and onshore converter stations. Compared with Scheme 1, the cost of independent planning is significantly reduced in

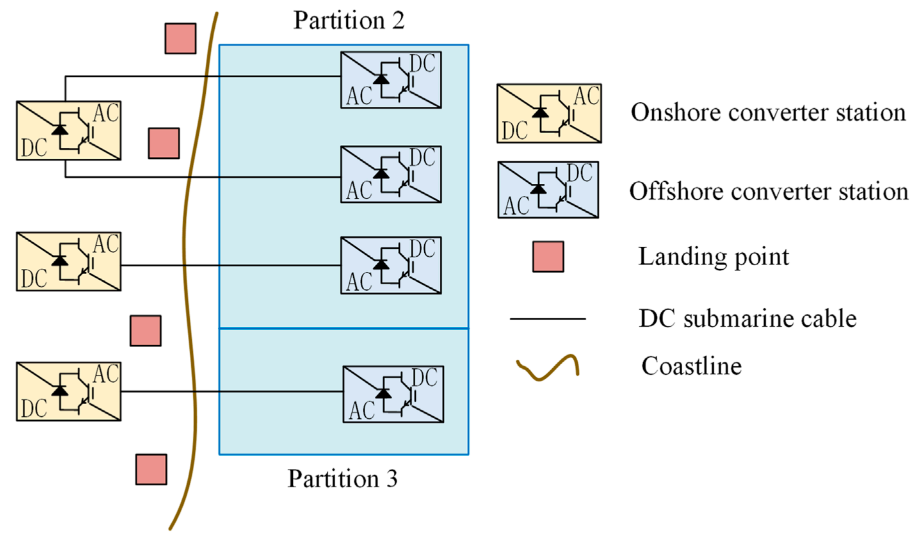


FIGURE 8
Diagram of the planning results based on Scheme 3.

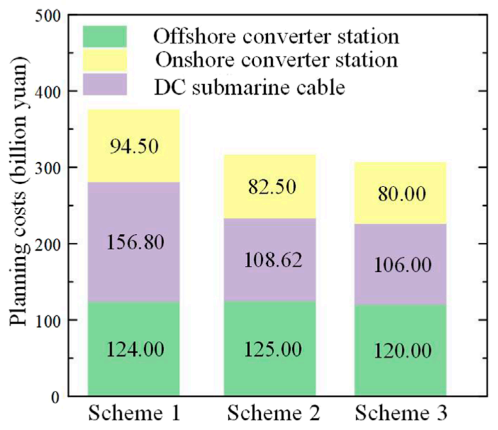


FIGURE 9
Planning costs based on the three schemes.

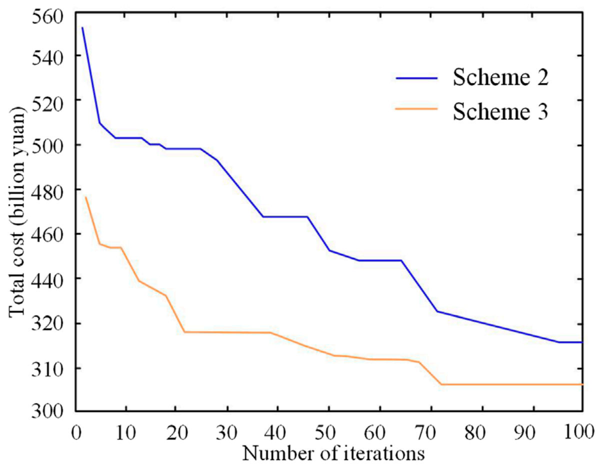


FIGURE 10
Comparison of convergence curves for different schemes.

Scheme 2. This is attributable to the number, locations, and types of the offshore converter stations that are based on the lower-layer model for planning of the transmission cables and other equipment via continuous optimization iteration. Synergistic optimization of the partitioned SLOWF through the VSC-HVDC system allows transmission of the planning results, so the total costs of partitioned SLOWF planning are reduced. Based on Scheme 2, Scheme 3 entails setting the initial parameters and the use of the SGA combined with K-means clustering to achieve a solution for the double-layer model. Table 1 shows that the number of offshore converter stations is fewest in Scheme 3, corresponding to the ability to choose larger capacity models for the offshore converter stations. Here, the onshore converter stations, DC submarine cables, and offshore converter stations are consistent with the 500 kV level. This not only reduces the cost of planning of the offshore converter stations but also decreases the costs of DC submarine cables and onshore converter stations. In conclusion, the planning method proposed herein entails the lowest cost and is economically optimal.

Next, we compare the convergence efficiencies of Schemes 2 and 3 that use the SGA. When the number of iterations and number of populations of both schemes are identical, the convergence curves for their planning costs are as shown in Figure 10. From Figure 10, we see that the convergence rate of Scheme 2 is significantly lower than that of Scheme 3. This is because Scheme 2 directly adopts the SGA to optimize the number, types, and locations of the offshore converter stations by setting the initial parameters randomly. Based on the proposed solution with the algorithm-generated scheme, we see that the combination of DPADN and SGA exhibits significant advantages, as shown in Table 2. Compared to particle swarm optimization (PSO), the method proposed herein effectively avoids local optima

TABLE 2 Comparison of different optimization algorithms.

| Algorithm | Computational complexity | Convergence rate | Ability to handle large problems |
|---|---|---|---|
| Segmented genetic algorithm | Low | Fast | Strong |
| Particle swarm optimization | Medium | Medium | Medium |
| Non-dominated sorting genetic algorithm II | High | Slow | Medium |
| Mixed-integer linear programming | High | Slow | Weak |

through adaptive division of the search space. Compared to the non-dominated sorting genetic algorithm II (NSGA-II), the introduction of DPADN enhances targeted handling of the dynamic constraints and reduces computational redundancy. Compared to the mixed-integer linear programming (MILP) method, the proposed approach accurately characterizes the non-linear dynamic constraints while significantly improving the solution efficiency for large-scale planning problems and ensuring accuracy by virtue of the heuristic search feature. Since the position coordinates are continuous variables, the algorithm converges more efficiently in Scheme 3 than the iterative process. In this work, the DPADN is used for initial parameter setting of the offshore converter stations to reduce blind search. Then, the double-layer coordinated planning model is solved using a combination of the SGA and K-means clustering algorithm. This greatly simplifies the complexity of optimization using only the genetic algorithm while solving the dependence of the K-means on the artificial preset parameters; hence, the convergence efficiency of the proposed Scheme 3 is higher.

## 5 Conclusion

To address the mismatches between large-scale development of SLOWFs and accommodation capacities of onshore power grids, we propose a transmission system planning method for partitioned SLOWFs. Based on our simulation analysis and comparative verification, the following conclusions are drawn. Considering the limited accommodation capacity of offshore wind power, the SLOWF is partitioned using DPCA with an accommodation constraint mechanism. The generated power is then transmitted to different onshore power grids to achieve more efficient accommodation. Herein, we constructed a double-layer planning model for the transmission system of a partitioned SLOWF by enabling coordinated planning of the main equipment like offshore converter stations, DC submarine cables, and onshore converter stations. Our simulation results indicate that the proposed model can effectively reduce the total investment cost of the transmission system for partitioned SLOWFs. To improve the planning and solution efficiency, we combined the DPADN with the SGA in this study for optimization. This approach effectively overcomes the dependency of the K-means algorithm on the initial parameters as well as the inefficiency of traditional genetic algorithms, thereby enhancing the convergence efficiency and optimization performance. As the emergency situation concerning power systems is a complex research direction, our future research efforts will be focused on developing a more robust model framework by incorporating uncertainty factors into the objective function and constraints, thereby enhancing the stability of this research outcome further. Considering the limited literature support available currently, comparative analyses of different algorithms will also be carried out in future studies.

## Data availability statement

The data are available from the corresponding author upon reasonable request.

## Author contributions

LX: Writing – original draft, Writing – review and editing. MZ: Writing – original draft, Writing – review and editing. XZ: Writing – review and editing, Writing – original draft. LZ: Writing – review and editing, Writing – original draft. JL: Writing – original draft, Writing – review and editing. XB: Writing – review and editing, Writing – original draft.

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## Conflict of interest

Authors LX, MZ, XZ, and LZ were employed by the East China Grid Company Limited.

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

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