Research on Generation and Transmission Expansion Planning Method for Large-Scale Islanded Renewable Energy System Connected to Flexible DC

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***Abstract*—With the rapid development of new renewable energy generation technologies in the world, the problem of wind and solar power curtailment is becoming more and more serious. Therefore, to improve the capacity of absorbing new energy, in this paper, we propose a generation and transmission expansion planning method for the scenario of new energy island transmission by flexible DC. First, considering the effect of the number, site selection and voltage levels on the operational characteristics of the power system, a topological optimization scheme is proposed to converge renewable energy accommodation. Second, the capacity optimization method and the grid structure scheme for the converter stations of the flexible HVDC system are studied by considering the transmission capacity, the voltage limit and the capacity of the collection stations. Finally, multi-objective and multi-constraint network-source collaborative planning model is established.**

Keywords—renewable energy accommodation, generation and transmission expansion planning, DC convergence, capacity planning

I. Introduction

The isolated island power grids are restricted by geographical conditions and difficult to interconnect with large power grids, so they are characterized by small loads, weak power sources, large active fluctuations, and obvious voltage fluctuations, which make it difficult to guarantee the power supply reliability, security, and stability [1]. Large-scale new energy clusters using flexible DC delivery is a research hotspot in recent years, because flexible DC can solve the problem of large-scale delivery of new energy under the conditions of weak AC system at the delivery end [2-3].

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Researchers have conducted a lot of studies on the topology, control method, control protection and other aspects of flexible DC [4-7], but there is still insufficient research on the matching selection of flexible DC application type in different scenarios. Reference [8] proposed a joint optimization model of sending end converter station. In terms of new energy DC convergence, scholars currently mainly take offshore wind power as the application scenario [9-11], while the research on DC convergence system for onshore large-scale new energy power generation bases is still relatively small. Reference [12] studied a parallel DC convergence system for offshore wind farms, and analyzed its network architecture, system control, and high-voltage DC/DC converter technology. Reference [13] studied a large-scale onshore new energy cluster DC convergence and transmission scenario, and explored its grid topology, transmission capacity, voltage level and other key technologies.

In terms of the network source coordination planning model for new energy island transmission by flexible DC, the topology, voltage level and converter station capacity of the collection station have an important impact on the power limit of the new energy sending and the stable operation of the system [14-16]. In this paper, the topology optimization scheme of new energy islanding collection is proposed by comprehensively considering the new energy sending demand, the construction cost and operation cost of DC convergence network. At the same time, the capacity optimization method and network structure scheme of converter station of flexible DC transmission system are studied, the network source cooperative planning model with optimal security and economy is established, and typical scenarios are selected for example verification.

II. TOPOLOGICAL OPTIMIZATION SCHEME FOR DC CONVERGENCE

A. Linearized Model of Curtailment POWER Costs

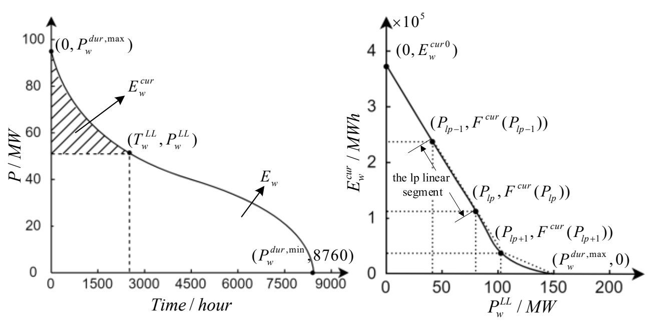
The annual power curtailment of the new energy power plant E_w^{cur} is calculated by (1), respectively, where $P_w^{dur,\min}$ and $P_w^{dur,\max}$ are the annual maximum and minimum output of the new energy power plant, respectively.

$$E_w^{cur} = \begin{cases} 0, & P_w^{LL} \ge P_w^{dur,\max} \\ \int_0^{T_w^{LL}} P_w^{dur}(t)dt - P_w^{LL}T_w^{LL}, & 0 \le P_w^{LL} < P_w^{dur,\max} \end{cases} \tag{1}$$

According to the relationship between the annual generating capacity of the new energy power station, the annual power generation and the annual power curtailment, the annual power generation is:

$$E_w = E_w^0 - E_w^{cur} = \int_0^{8760} P_w^{dur}(t)dt - E_w^{cur} \tag{2}$$

Fig. 1(a) depicts the annual continuous output curve of a new energy power plant, and it can be seen that the annual continuous output of the new energy power plant is a monotonous decreasing function of the cumulative duration. According to the definition of the annual sustained output curve and equation (1), E_w^{cur} changes with P_w^{LL}, as shown in Fig. 1(b).



(a) Annual active output curve (b) Power curtailment curve

Fig. 1. Linearization of power curtailment costs

In order to deal with the nonlinear relationship between E_w^{cur} and P_w^{LL}, the annual power consumption curve of the new energy power plant in Fig. 2 can be linearized into segments for approximation. In the definition domain of P_w^{LL}, $N_1^{seg}+1$ points are selected to divide the annual power curtailment curve into N_1^{seg} linear segments, where the definition domain of the lp linear segment is $[P_{lp-1}, P_{lp})$. Therefore, (1) can be approximated by (3), where $f_{w,lp}$ is the slope of the lp linear segment and $\Delta P_{w,lp}$ is the decision variable of the lp linear function.

$$\begin{cases} E_w^{cur} = E_w^{cur0} + \sum_{lp} f_{w,lp}\Delta P_{w,lp} \\ f_{w,lp} = \dfrac{F^{cur}(P_{w,lp}) - F^{cur}(P_{w,lp-1})}{P_{w,lp} - P_{w,lp-1}}, \quad \forall w \\ 0 \le \Delta P_{w,lp} \le P_{w,lp} - P_{w,lp-1} \quad P_w^{LL} = \sum_{lp} \Delta P_{w,lp} \end{cases} \tag{3}$$

B. Linearized Model for Collection Station Siting

The line length mainly depends on the relative distance between the collection station site and the new energy power station location. In order to linearize the line length, this section rasterizes the construction area of the collection station into m raster cells, and the location of the center of each raster cell on the map is taken as the candidate address of the collection station. According to (4), the distance parameter $L_{i,m}$ between the raster m and each wind farm cluster and the distance parameter $L_{m,n}$ between this raster and the convergence station can be obtained.

$$\begin{cases} L_{i,m} = \sqrt{(x_i - x_m)^2 + (y_i - y_m)^2} \\ L_{m,n} = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2} \end{cases} \tag{4}$$

The binary variable $b_{j,m}$ is used as the decision of whether or not the collection station j is built at raster m. When $b_{j,m}$ is 1, it means that the site of the collection station *j* is at raster m. Conversely, the site of the collection station *j* is not at raster m. Then there are:

$$0 \le \sum_j \sum_m b_{j,m} \le N^w \tag{5}$$

The length $L_{i,j}$ of the line from the wind farm cluster to the collection station and the length $L_{j,n}$ of the line from the collection station to the converter station can be described as a linear equation with respect to $b_{j,m}$.

$$\begin{cases} L_{i,j} = \sum_m b_{j,m} L_{w,m} \\ L_{j,n} = \sum_n b_{j,m} L_{m,n} \end{cases} \tag{6}$$

In addition, in order to ensure that the raster map-based approach for the siting of the collection stations is equivalent to the original problem, it is necessary to avoid the situation in which there are multiple siting of a collection station as well as the situation in which multiple collection stations have the same siting. Therefore, the model must also satisfy (7) and (8).

$$\sum_m b_{j,m} \le 1, \forall j \tag{7}$$

$$\sum_j b_{j,m} \le 1, \forall m \tag{8}$$

C. Restrictive Conditions

1) Power Blance Constraint

The power balance constraint means that at any time t, the theoretical output of the new energy field should be equal to the sum of the discarded power and the line power, as shown in (10), where $P_{t,wind}$, $P_{t,cur}$ and $P_{t,line}$ are the theoretical output of the new energy field, the discarded power and the line power at the moment t, respectively.

$$P_{t,wind} = P_{t,cur} + P_{t,line} \tag{9}$$

2) Capacity Constraints

The collection station capacity constraint means that the collection station should be constructed with a configured capacity that is greater than the electrical power being converged. The capacity constraint of the collection station is shown in (11), where P_{col} is the configured capacity of the collection station, $b_{i,j}$ is the 01 variable of whether wind farm *i* is connected to collection station *j*, and $P_{i,line}$ is the line power on the line connected to wind farm i.

$$\begin{cases} P_{col} \geq \sum b_{i,j} \cdot P_{i,line} \\ \sum b_{i,j} = 1 \end{cases} \tag{10}$$

3) Constraints on the Construction District

Due to constraints such as geographic conditions, the construction district of collection stations is not randomly selected, but is specified within a fixed district, whose constraints are shown in (11), where x_{col} and y_{col} are the coordinates of the site selection of the collection station and $x_{\min}$, $x_{\max}$, $y_{\min}$ *and* $y_{\max}$ are the boundary of the buildable district.

$$\begin{cases} x_{\min} \leq x_{col} \leq x_{\max} \\ y_{\min} \leq y_{col} \leq y_{\max} \end{cases} \tag{11}$$

4) Grid connection constraints

In order to ensure that each wind cluster is able to send power in normal grid-connected operation, the variable $b_{i,j}$ that determines the connection of the wind cluster to the collection station must satisfy (12).

$$\sum_j b_{i,j} = 1, \forall i \tag{12}$$

At the same time, in order to ensure the grid-connected operation of wind farm clusters, the variable $b_{j,n}$ that determines the grid-connection from the collection station to the converter station must satisfy (13).

$$\sum_n b_{j,n} = 1, \forall j \tag{13}$$

In addition, the number of collection stations to be constructed in the planning is determined by the actual demand for grid connection of wind farm clusters. Therefore, the constraint on the number N^{HS} of collection stations to be constructed is shown in (14), where N^w is the total number of wind clusters.

$$0 \leq N^{HS} \leq N^w \tag{14}$$

III. Capacity Optimization Model for Converter Stations

A. Cost Modeling for the Construction of Converter Stations and Transmission Lines

The construction cost of a converter station is closely related to its configured capacity. Therefore, the cost of converter station construction can be considered to be linearly related to the configured capacity. C_{conv}, P_{conv}, and K_{conv} are converter station construction costs, configured capacity, and construction cost factors, respectively.

$$C_{conv} = K_{conv} P_{conv} \tag{15}$$

In the actual engineering of new energy grid-connected transmission, the line construction cost per unit length can be regarded as a graduating function of transmission capacity. Therefore, the linearized expressions for the unit length construction cost function $F^{LL}(S_w^{LL})$ for the wind farm cluster outlet line and the unit length construction cost function $F^{HL}(S_{j,n}^{HL})$ for the grid-connected line of the collection station are (16) and (17), respectively. The subscripts *ll* and *hl* denote the wind farm cluster export line and the grid-connected transmission line of the collection station, respectively.

$$\begin{cases} F^{LL}(S_w^{LL}) = \sum_{ll} b_{w,ll}^{LL} c_{ll}^{LL} \\ \sum_{ll} b_{w,ll}^{LL} = 1 \\ S_{ll-1}^{LL} - K(1-b_{w,ll}^{LL}) < S_w^{LL} \leq S_{ll}^{LL} + K(1-b_{w,ll}^{LL}) \end{cases} , \forall w \tag{16}$$

$$\begin{cases} F^{HL}(S_{j,n}^{HL}) = \sum_{hl} b_{j,hl}^{HL} c_{hl}^{HL} \\ \sum_{hl} b_{j,hl}^{HL} = 1 \\ S_{hl-1}^{HL} - K(1-b_{j,hl}^{HL}) < S_{j,n}^{HL} \leq S_{hl}^{HL} + K(1-b_{j,hl}^{HL}) \end{cases} , \forall j \tag{17}$$

Combining the construction cost function of the transmission line with the length function, the linearized expression for the cost of the transmission line can be obtained as:

$$\begin{cases} C_{w,j}^{LL} = \sum_{ll} b_{i,j,ll} c_{ll}^{LL} L_{w,j} \\ b_{i,j,ll} \leq b_{i,j} \\ b_{i,j,ll} \leq b_{j,ll} \\ b_{i,j,ll} \geq b_{i,j} + b_{j,ll}^{LL} - 1 \end{cases} , \forall i, j \tag{18}$$

B. Restrictive Conditions

1) Power Balance Constraint

At any moment, the line power should be equal to the power received at the converter station.

$$P_{t,conv} = P_{t,line} \tag{19}$$

2) Converter Station Capacity Constraint

The capacity of the converter station should be greater than the sum of the electric power flowing into the converter station.

$$P_{conv} \geq \sum P_{j,line} \tag{20}$$

3) Power Limit Constraints of Flexible Direct Network

The total capacity of all converter stations should be less than the power limit of the flexible network.

$$P_{conv} \leq P_{vscnet,\max} \tag{21}$$

IV. Flexible DC Grid Planning Model

A. Flexible DC Transmission Cost Modeling

The cost per unit length of construction of a transmission line can be viewed as a graduating function of substation capacity or transmission capacity. A binary variable b is set for each capacity segment, and when b is 1, it indicates that the line capacity is located in that capacity segment.

$$\begin{cases} K_{line}(P_{line}) = \sum_{ll} b_{line,ll} C_{line,ll} \\ \sum_{ll} b_{line,ll} = 1 \\ P_{line,ll-1} - K(1 - b_{line,ll}) < P_{line} \leq P_{line,ll} + K(1 - b_{line,ll}) \end{cases} \tag{22}$$

The coordinates of the converter station and the receiving end of the flexible grid are known in this section, so the distance equation can be used to directly find the transmission line cost. S_{pq} and L_{pq} denote the power capacity and transmission distance from the converter station to the receiving end, respectively. b_{pq} can only take two numbers, 0 or 1. When it is 0, it indicates that the converter station is not connected to the receiving end and when it is 1, it indicates that the converter station is connected to the receiving end.

$$L_{pq} = \sqrt{(X_p - X_q)^2 + (Y_p - Y_q)^2} \tag{23}$$

$$C^{LL} = \sum_{p=1}^{n} \sum_{q=1}^{m} b_{pq} S_{pq} L_{pq} \tag{24}$$

B. Restrictive Conditions

In order to ensure that each converter station sends power and each receiving end receives power delivery, the following constraints should be satisfied:

$$\begin{cases} 0 \leq b_{pq} \leq 1 \quad \forall p, \forall q \\ \sum_{q} b_{pq} = 1 \quad \forall p \end{cases} \tag{25}$$

The capacity of each converter station to be transmitted to the receiving end should be equal to the capacity that the converter station itself has and cannot exceed the capacity of that converter station. Therefore, each converter station capacity constraint is:

$$\begin{cases} \sum_{j=1}^{m} S_{p_i q_j} = S_{p_i} \\ \vdots \\ \sum_{j=1}^{m} S_{p_n q_j} = S_{p_n} \end{cases} \tag{26}$$

In addition, each receiving end cannot accept more capacity than itself requires. Therefore, the capacity constraint of each receiving end is:

$$\begin{cases} \sum_{i=1}^{n} S_{p_i q_1} = S_{q_1} \\ \vdots \\ \sum_{i=1}^{m} S_{p_i q_n} = S_{q_m} \end{cases} \tag{27}$$

V. Network-source Cooperative Planning Model

Based on the power balance constraints, convergence station construction district constraints, grid connection constraints, a new energy cluster convergence topology optimization model, a flexible DC converter station capacity optimization model, and a flexible DC grid planning model are established. On the basis of ADMM distributed optimization algorithm, multi-layer planning theory is applied, and constraints such as line transmission capacity, voltage, power and converter capacity are fully considered, and the complete planning scheme is finally obtained by hierarchical solving with the goal of minimizing economic cost. The net-source cooperative planning solution flow is shown in Fig. 2:

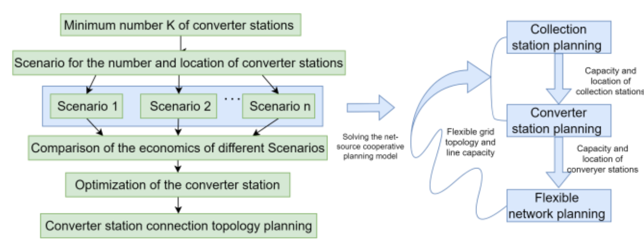


Fig. 2. Network-source Cooperative Planning Model

Due to the large scale of planning solution, a hierarchical solution model is adopted. Considering the coupling between the various layers of planning, in order to reduce the complexity of the model, first of all, the number and location of the converter station as a known condition, the location of the converter station under this scheme is substituted into the convergence station converter station joint planning program to obtain the capacity of each converter station. Then, according to the capacity, number and location of the converter stations, and under the premise of known load demand and location of the receiving end, substitute into the flexible network planning model, and solve to obtain the network framework and capacity of each converter station and the line between the receiving end, i.e., how many outgoing lines are there in each converter station, and to which receiving end are they connected. Through the above steps to complete the current number of converter stations under the convergence station, converter station, flexible straight network planning results. After changing the number of converter stations, repeat the above steps to get the planning result under another scheme. By comparing the total cost under different number of converter stations, the economically optimal planning scheme can be obtained.

VI. Case Study and Results

The large-scale new energy clusters in a certain region are accessed via flexible DC access system as an example of network source synergistic planning illustration. The wind and solar power stations in the region are divided into six clusters, and the new energy clusters are equalized, and the geographic distribution map after equalization is shown in Fig. 3. The location of each cluster equivalent and the size of the installed capacity are shown in Table I.

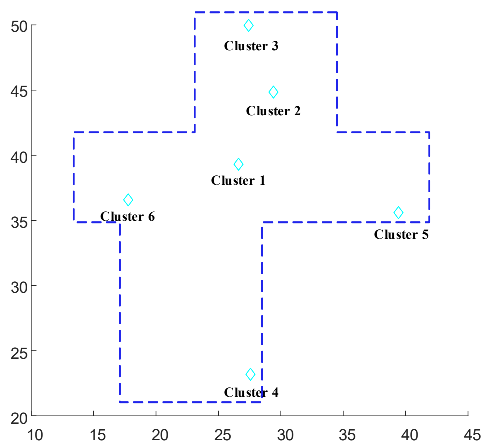


Fig. 3. Location of clusters

TABLE I. The Location of Each Cluster Equivalent and the Size of the Installed Capacity

	Capacity	Location
Cluster 1	3700MW	(26.6，39.3)
Cluster 2	3100MW	(29.4，44.9)
Cluster 3	2700MW	(27.4，49.9)
Cluster 4	2000MW	(27.6，23.2)
Cluster 5	2600MW	(39.4，35.6)
Cluster 6	3600MW	(17.8，36.6)

For the line cost of 110 kV, take the length of 100 km as an example, and draw the total cost curve according to the substation and transmission line engineering cost table as shown in Fig. 4. From the curve, it can be seen that the optimal design scheme corresponding to a certain transmission capacity has basically a certain cost in a certain interval. When the transmission capacity exceeds the rated capacity of the current scheme, it is necessary to use methods such as changing the design capacity of the substation or changing the line type and the number of line returns to improve its overall transmission capacity.

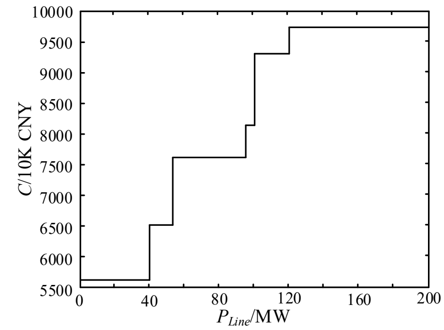


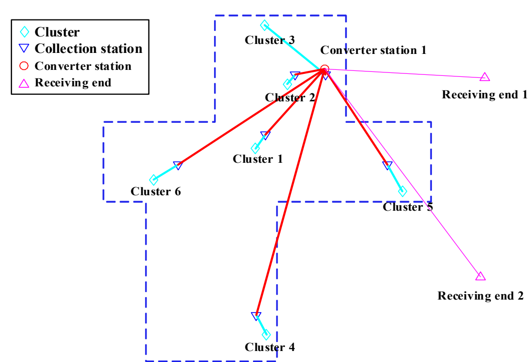
Fig. 4. Transmission line cost curves

Combined with the above solution process, first determine the number and location of the converter station, combined with the actual situation of the grid, the formulation of four scenarios, as shown in Table II.

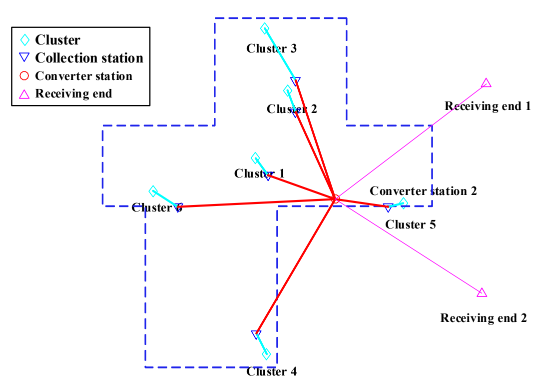
TABLE II. Location of Converter Stations Under Each Scenario

	Converter station 1	Converter station 2	Converter station 3
Scenario 1	(33.5, .9)		
Scenario 2		(32.6, .2)	
Scenario 3	(33.5, .9)	(32.6, .2)	
Scenario 4	(33.5, .9)	(32.6, .2)	(27.9, 8.5)

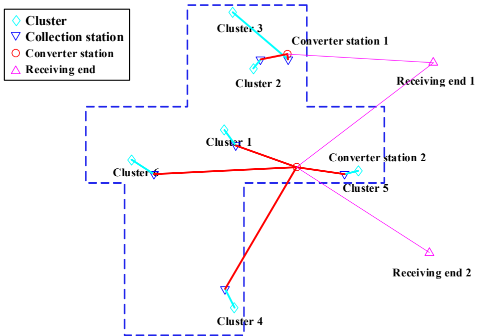
According to the network-source cooperative planning method proposed in this chapter, the planning schemes under the four converter station scenarios can be obtained. The results of collection station siting and flexible network planning for the four schemes are shown in Fig. 5.



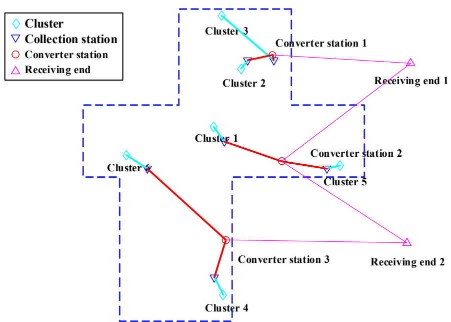
(a) Scenario 1



(b) Scenario 2



(c) Scenario 3



(d) Scenario 4

Fig. 5. Map of Planning Results under Different Scenarios

For easy observation, the cost of the line from the collection station to the converter station, the cost of the converter station construction, the cost of the line from the wind farm to the collection station, and the cost of the converter station to the flexi-grid construction are denoted by C1, C2, C3, and C4, respectively. The economic comparison of the four scenario is shown in TABLE III.

TABLE III. ECONOMIC COMPARISON OF THE FOUR SCENARIO

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
C1	269,420	280,410	195,720	136,060
C2	3,406,100	3,406,100	3,486,100	3,566,100
C3	86,753	98,446	92,243	92,243
C4	348,870	397,720	309,570	361,620
TC	4,111,143	4,182,676	4,083,633	4,156,023

A converter station can't consider the rational collection of wind resources in the whole region, and it is inevitable that the new energy field is far away from the converter station, thus greatly increasing the cost of the line, which results in a reduction of the economy. Therefore, the economy of Scenario 1 and Scenario 2 is the lowest.

Compared to the option with 2 converter stations, the installation of 3 converter stations reduces the line capacity to a certain extent, but it cannot offset the additional cost caused by the number of lines. Therefore, the cost of the lines between the converter stations and the receiving end in Scenario 4 is significantly larger than that in Scenario 3.

In summary, for the case of this new energy example, Scenario 3 is the optimal planning scheme.

VII. CONCLUSION

In this paper, for the planning model for new energy island transmission by flexible DC, the key factors affecting the economic efficiency of the planning model are investigated, and a network-source synergistic planning model is proposed and simulated for verification.

(1) The output characteristics of the new energy power station are analyzed, and the nonlinearized output curve is segmented and linearized. The rasterization method is used to determine the site selection of the collection station, and the non-convex planning problem is transformed into convex planning.

(2) Rational planning of capacity delivery is carried out to determine the connection relationship of the network frame and the transmission power of each line, and various costs are considered comprehensively to optimize the economy.

(3) Applying the multilayer planning theory, a network source cooperative planning model with multiple constraints is established to optimize the capacity of the sending end converter station and the network structure of flexible system.

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