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A Coordinated Restoration Method of Hybrid AC/DC Distribution Network for Resilience Enhancement

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***Abstract*- In recent years, the frequent occurrence of extreme natural disasters has caused huge economic losses, which makes it extremely important to improve the resilience of distribution networks. With the increasing penetration of DC sources and loads, the urban distribution network is transitioning from AC to hybrid AC/DC configuration that can operate in a ring structure. The features of flexible interconnections and low network losses of DC lines can break the bottleneck of traditional restoration methods for AC distribution networks under extreme disasters, thereby further enhancing the resilience of distribution networks. Based on the interconnection feature of DC lines, this paper proposes a topology search strategy with DC lines as the core to realize the joint recovery of multiple power sources and multiple critical loads. With the obtained interconnection topology after topology search, a fault restoration model for maximizing the resilience index is established. To ensure the generality of the proposed model and explore the advantages of flexible DC power control, this paper transforms the objective function from the complex model into a mixed integer second-order cone programming (MISOCP) that can be solved directly. The optimal restoration strategy for resilience enhancement of AC/DC hybrid distribution networks can be obtained by solving the proposed MISOCP model. The numerical results in case study validate the effectiveness and superiority of the proposed method.**

***Index Terms*--Hybrid AC/DC, distribution network, resilience, coordinated restoration.**

I. Introduction

Loads in urban distribution networks require high reliability of power supply. However, frequent natural disasters in recent years have raised concerns about classical power system reliability perspectives [1]. Critical loads in distribution networks, including hospitals, street lighting, water stations, as well as other key infrastructures, can encounter long-time service interruptions during such extreme events, which can cause significant economic losses. Resilience is used to evaluate the capability of critical load restoration under natural disasters. Considering the increasing frequency and severity of such extreme events due to the climate change, it is necessary to enhance the resilience of distribution networks.

Several methods have been proposed to effectively enhance the resilience of distribution networks, such as strengthening basic infrastructures [2], optimal allocation of distributed generation (DG) and energy storages [3], optimizing the deployment of repair crews, generator and topology switch [4], and DG-based restoration strategies [5]. Among them, the restoration strategies based on DGs play an important role on resilience enhancement for distribution networks, which are closely related to the recovery efficiency and the amount of recovered critical loads in the restoration process.

Existing research of load restoration in AC distribution networks mainly focused on the reconfiguration of network integrated with DGs and energy storages. However, under extreme events, after disconnecting with the utility grid, loads can only be restored by the emergency power sources or local DGs with energy storage. In addition, feasible restoration topologies are limited due to the radial operation constraints of AC distribution networks and line destructions under extreme events. For example, in [6], a resilience-oriented strategy by building multiple microgrids through changing the switches status to restore critical loads was proposed, considering the radial operation constraints. In [7], the concept of dynamic boundary microgrid was proposed that divided a blackout distribution network into several microgrids, whose boundaries can be dynamically adjusted. Failure isolation and load restoration could therefore be achieved. In [8] and [9], the emergency operation mode of microgrids under extreme events to restore critical loads were studied. In [10] and [11], the method by using the extra energy of a microgrid to restore critical loads outside considering the AC voltage stability and frequency issues was proposed.

Due to the limited effective solutions concerning the radial operations in AC distribution networks [6]-[11], the capability of emergency power sources cannot be fully utilized to maximize the number of critical loads that can be recovered. Coordinating multiple emergency power sources during the restoration could be an option to extend the continuous power supply of critical load by energy sharing and complementarity. However, fully utilizing the capability of emergency power sources is still very challenging for traditional AC distribution

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networks, as the demand curve of critical loads usually cannot accurately match the output of the specific emergency source.

Moreover, the restoration of critical loads after extreme events can also be limited by the maximum power transfer capacity and voltage drops of power lines during the restoration process. Survival time of critical loads can be further shortened under insufficient emergency energy if extra power losses of lines occur during the restoration.

Therefore, the bottleneck of the radial operation constraint is expected to be overcome so that multiple critical loads can be restored by multiple emergency power sources simultaneously. Meanwhile, the capabilities of distribution network restoration including voltage performance, maximum transfer power capability, and line power losses need to be enhanced to meet the power flow constraint during restoration. DC distribution lines possess several unique advantages over the AC alternatives, such as higher line transfer capabilities, smaller voltage drops and line power losses [12], [13]. Besides, DC distribution lines can operate in the loop mode without considering the influences of frequency and voltage phase [29], [30]. Therefore, multiple critical loads can be served by multiple emergency power sources simultaneously through the interconnected DC lines during the restoration process. In [26]-[28], the authors studied the application of DC power distribution technology in microgrids. Among them, [26] proposed a planning model considering the type of microgrid (AC/DC), the conclusion of which is that the decisive factor for determining the type of microgrid is whether the proportion of DC load exceeds the calculated threshold proportion. In [27], the planning of expanding the DC lines within AC microgrid was studied, which especially considered the effect of suppressing the fluctuation of charging load including electric vehicles in the objective function. In [28], the planning results of pure AC microgrid with that of AC/DC hybrid microgrid have been compared, which showed that the additional consideration of the DC component makes the planning results more economical. In [29] and [30], the authors studied the interconnection of multiple distribution networks through new DC lines to improve the power handling capacity of the original distribution network. Among them, [29] introduced the use of DC lines to connect several urban distribution networks to improve reliability and expand operational flexibility in load-intensive areas. Besides, a cost-benefit assessment of the interconnection of such complex distribution networks has been conducted. In [30], the method for realizing the flexible control of power flow through the connection of DC lines was proposed, which was more economical to apply in a long radial distribution network with dense loads and distributed power sources.

Hybrid AC/DC technology have been widely-used for high-voltage transmissions [14], distribution networks [15], and low-voltage microgrids [16]. Conversion of existing AC lines to DC operations has been presented in the CIGRE report to enhance the power transfer capability and DG accommodation [17]. Hybrid AC/DC distribution networks are the potential solutions to break the bottleneck of critical loads restorations in traditional AC distribution networks for resilience enhancement if the DC devices such as voltage source converters (VSCs) and DC lines are available after the extreme events.

However, due to the innate topological differences, the full restoration potential of hybrid AC/DC distribution networks under extreme events cannot be fully exploited if the existing methods for AC distribution systems are directly applied, resulting in missing some of the feasible solutions. Therefore, the best restoration topology and control method of hybrid AC/DC distribution networks need to be explored to achieve the maximum power supply for critical loads.

On the other hand, the existing studies on fault recovery of AC/DC hybrid distribution networks hardly consider the scenarios of extreme disasters, where most of the fault types are only the single point network failure and mainly rely on the main network for recovery. In [31], the authors established a complex mixed integer nonlinear programming model aiming at minimizing the load, capacity, and losses, and proposed a recovery strategy considering the active and fast power flow regulation capability of variable structure control elements. However, the recovery method is solely based on the main network. In [32], the authors proposed a coordinated fault recovery strategy among the master station, flexible DC control system, and protection devices according to the operation characteristics of flexible interconnected distribution networks. An analysis model of the power supply capability of the flexible DC device with passive load was established. However, this recovery strategy is not suitable for scenarios with limited power supply resources, e.g., under extreme events. In [33], the authors proposed a coordinated restoration method of AC/DC hybrid distribution network with electrical buses (EBs), established a two-layer model, and optimized the network reconfiguration, VSC output and EBs scheduling scheme simultaneously to obtain better power transfer capability for load restoration. However, the model has not considered the energy scheduling issue of distributed power generation.

There are three main challenges associated with the model establishment and solution method on developing the restoration strategies for hybrid AC/DC distribution networks under extreme events:

(1) Generation of the restoration topology. The restoration topology of the hybrid AC/DC distribution network is different from the traditional AC restoration topology. Due to the existence of DC lines that can be interconnected, the number of feasible solutions is greatly increased. Besides, just being physically connectable does not guarantee that the operational requirements of the network can be satisfied. In the restoration process of hybrid AC/DC system, the operational constraints of power flow in both AC lines and DC lines need to be considered, as well as the VSC capability for power flow regulation. Besides, since critical loads have different priority levels and supply period requirements, while the available power energies in multiple periods are changing with different restoration topology and control method, the optimization of restoration topology and control method must

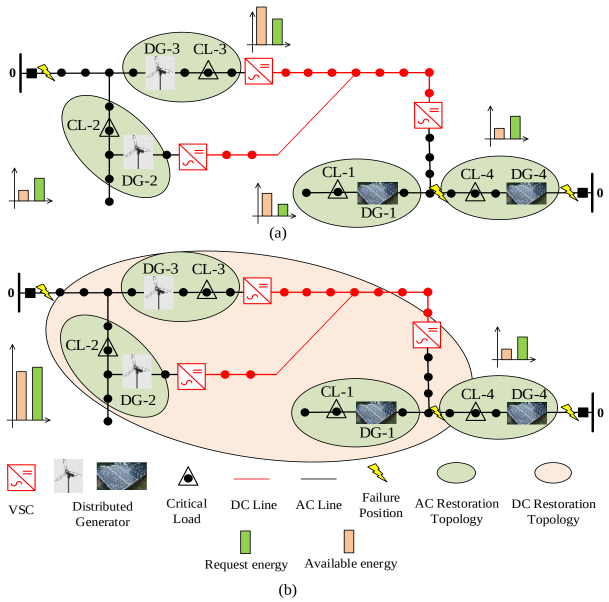

Fig. 1. Topology results with (a) conventional method under radial constraint, (b) proposed topology search method considering DC interconnections.

be considered simultaneously.

(2) Energy aspect of the restoration model. The existing restoration strategy of the hybrid AC/DC distribution network is mainly based on the main network. However, in extreme events, the main network mostly loses its power supply capacity, and the number of resources in the network is also limited. As a result, the optimal allocation of the available energy inside the network needs to be additionally considered during the establishment of the restoration model. There is also a coupling relationship between the operating state of the system and the available energy of the system that both affect the model, which would increase the difficulty of solving the model and guarantee the optimality of the feasible solution. Therefore, it is necessary to establish an accurate and solvable restoration model.

(3) Model solving algorithm. The restoration model for hybrid AC/DC system is usually formulated as a nonlinear mixed integer model, where an efficient algorithm is needed that considers the interconnected AC/DC restoration topology. However, the heuristic algorithm fails to guarantee the stability and convergence of the solutions [18], while the relaxation errors will be large if a mathematical programming method is used such as second-order cone programming, since the objective of restoration in this paper is not an increasing function of branch current [19].

In this paper, a resilience-oriented coordinated restoration method for hybrid AC/DC distribution networks is proposed. Firstly, a preliminary topology search method is developed considering DC lines as the emergency paths. Then, the two-step optimization model for load restorations that maximizes the resilience index is established. The optimal restoration scheme is finally obtained considering the power flow constraints and critical load requirements in multiple periods based on the optimization model for resilience enhancement.

The main contributions of this work are listed as follows:

(1) The proposed method can fully utilize the advantages of the convenient interconnections of DC lines. The solutions of restoration topologies that are mathematically correct but not feasible physically with conventional methods considering radial constraints are now valid in practice. As a result, the number of feasible solutions for restorations is significantly increased, and mathematical optimal solutions can be achieved with a higher resilience index. The computational efficiency is also enhanced without the repeatedly searching process.

(2) The proposed method can fully exploit the flexible power transfer between multiple restoration areas of the AC/DC hybrid distribution network, as well as the flexibility of DC power control. As a result, the priority restoration of critical loads with higher weighting factors can be guaranteed, which further improves the resilience index of distribution networks.

(3) The proposed method has a wider applicability. The conventional cone optimization methods require that the objective can only be current minimization and the restoration topology must be radial to ensure the convergence of solutions. The proposed method overcomes the limitation that the optimal restoration solution can only be obtained when the objective function is tightened after the cone optimization relaxation process. The case that the cone optimization cannot obtain a feasible solution in specific scenarios in solving the restoration model of hybrid AC/DC distribution networks is thus avoided with the proposed method.

II. Topology Search Method Considering DC Interconnections

After a natural disaster, the upper grid of a distribution network would usually lose its power supply capability. In case of such outages, a resilient distribution network should be able to quickly restore the critical loads that have been interrupted. For traditional AC distribution networks, the restoration methods are supposed to be operated under the radial topology constraints. Therefore, the final restoration topology is in the ‘single supply-load’ mode.

During the restoration topology search process of the traditional method, it first carries out the depth-first traversal of all single supply and single load paths over the entire searching space, then merges the paths that start from the same power supply. The optimal solution is finally determined by the restoration strategy. Take the distribution network in Fig. 1 (a) that contains three outages as an example, where the DG indicates the available power supply after a disaster, including photovoltaics (PV) panels, energy storage, and diesel generators, etc., and ‘CL-’ denotes the critical load. With conventional AC restoration methods, four islands for critical load restoration are formed. Each small bar represents the required energy and the available energy of critical loads in each restoration area. As shown in Fig. 1 (a), there are two restoration areas with energy redundancy. However, due to the independent operation of each island, it is impossible to achieve energy transfer between them.

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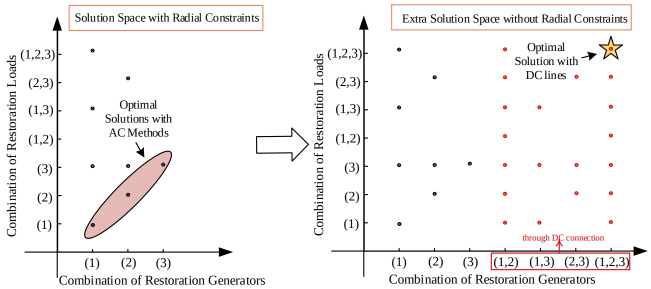

Fig. 2. The change of feasible solution space after considering the radial constraint.

Compared with the restoration methods for AC network, the restoration considering DC could benefit from the convenient interconnections of DC lines. During the restoration process, multiple power supplies can be interconnected using the DC lines. Therefore, the joint restoration of multiple power supply to multiple loads can be achieved, avoiding such scenarios that 1) the power supply and loads are close, but the power output curve cannot match the load curve, or 2) the power output curve matches the load, but the topology cannot be connected. Compared with the above scenarios that will cause the waste of supply or energy redundancy, the restoration that considers DC interconnections can maximize the resource utilization.

Take the same distribution network in Fig. 1 (b) with DC interconnections. After the radial operation constraint is relaxed, three of the four islands determined by the traditional AC method in Fig. 1 (a) can be interconnected through DC lines, where the most critical loads are restored with priority. As shown in the bars concerning the required energy and the available energy of critical loads in Fig. 1 (b), although the overall available energy is still less than the load demand, due to the interconnection capability of the DC lines, the flexible energy transfer can be realized, hence the energy consumption efficiency as well as the resilience index of the system can be improved accordingly.

In order to ensure the stable operation of the load, different control methods are supposed to be adopted for the various VSCs in the interconnection area. Among them, one VSC needs to be controlled by a constant DC voltage to ensure the stable operation of the DC lines, while the other VSCs would adopt PQ control to flexibly adjust the direction and amount of power transmissions, to realize the power mutual aids between multiple lines according to their energy surplus in multiple areas.

The optimization model for hybrid AC/DC distribution network restoration after a natural disaster is formulated as a mixed integer programming problem. The optimization model for hybrid AC/DC distribution network restoration after a natural disaster is formulated as a mixed integer programming problem. For conventional AC restoration methods, the radial constraints must be satisfied. By expressing the distribution network in the form of graph theory, the line can be represented by the arc in the graph theory, the load point and the power source point can be represented by the node in the graph theory. For graph theory, a dendrogram can be considered as a loop-free connected topology, hence the radial constraints of the distribution network can be expressed by the following two conditions:

Condition 1: There are N-N_s closed branches in the network.

Condition 2: There is no connected power supply loop in the network.

The mathematical expressions of the *Condition 1 and 2* are as follows [38]:

$$\sum_{b=1}^{B} x_b = N - N_S \tag{1}$$

$$\sum_{m=1}^{M_l} x_{lm} \le M_l \text{ -1} \tag{2}$$

where B is the total number of branches in the distribution network, b is the number of a branch. L is the total number of supply loop, M_i indicates the number of branches in supply loop l, x_{lm} represents the status of branch m in supply loop l.

As the proposed method with DC interconnections does not consider radial operation constraints in (1), (2), the number of feasible solutions for restoration will increase exponentially.

The feasible solutions of restoration topologies obtained by the traditional AC method as in Fig. 1 (a) and the proposed method as in Fig. 1 (b) considering DC interconnections are presented and compared in Fig. 2. As the traditional AC method needs to consider the constraints of radial operations, the space of feasible solutions has been greatly reduced, i.e., only those in the left-side in Fig. 2. With the proposed method, the feasible solution space has been enlarged greatly, i.e., the whole area in Fig. 2, and there exists an optimal solution with a higher resilience index. As shown in Fig. 2, after the radial constraint has been relaxed, the space of feasible solutions has been enlarged, and the solutions have become optimized. As a result, the optimal solutions obtained by the conventional method result in a mismatch between the power supply and loads in the restoration area (the power supply 1, 2, 3 corresponds to the restoration load 1, 2, 3, respectively). Such mismatch will lead to energy surplus or shortage in certain restoration areas. On the other hand, for the optimal solution obtained by the proposed method with DC interconnections, the power supply 1, 2, 3 and load 1, 2, 3 can be interconnected in one restoration topology. As a result, there will be no energy redundancy in the restoration process, thus the resilience of distribution networks can be improved.

However, the restoration topology obtained by this method is not necessarily the final restoration topology. Since the total energy available in the network is limited and less than that of the critical loads, it is not guaranteed that all loads can be restored finally. The restoration topology also depends on the energy distribution scheme. However, compared with the traditional AC restoration strategy, the topology search method proposed in this paper is still better due to the advantages of interconnected DC lines.

In summary, the solutions of restoration topology obtained by the proposed method with interconnected network are more and better than the 'single supply-load' case. To fully exploit the advantages of DC lines to facilitate interconnections and energy complementation, a novel topology search method for load restorations in hybrid AC/DC distribution networks is proposed. The detailed procedures are as follows:

1) 'Power Sources - DC Lines - Critical Loads' Path Search

The interconnection of multiple power sources mainly relies on the VSC, while the core of the interconnection area that to be recovered is the DC lines. If available power sources can fully be connected through DC lines, the maximum utilization of the sources for restoration can be achieved. Therefore, a "power sources-DC lines" path should be firstly established.

A simple non-vector graph $G = (V, E)$ with n nodes is used to represent the distribution network. The set of nodes in graph G is represented by $V = \{v_1, v_2, \ldots, v_n\}$, which mainly includes the source and load of distribution networks, as the starting point and the end point of the lines. And the set of branches that connecting nodes is represented by E, which is determined by the topology of distribution network. The node matrix of the power supply and the node matrix of the DC lines are established, as shown in (3) and (4), respectively.

$$V_{source} = \{v_{s1},\ v_{s2},\ v_{s3}, \ldots\} \tag{3}$$

$$V_{DC} = \{v_{d1},\ v_{d2},\ v_{d3}, \ldots\} \tag{4}$$

where v_{s1}, v_{s2}, and v_{s3} represent the nodes with source s_1, s_2, and s_3, and v_{d1}, v_{d2}, and v_{d3} represent the nodes with DC lines d_1, d_2, and d_3, respectively.

A complete model can be formulated with the graph theory models of distribution networks, where the electrical distance matrix from each power source to the DC line is established as

$$E(G)=\begin{bmatrix} d(v_{s1},v_{d1}) & d(v_{s1},v_{d2}) & d(v_{s1},v_{d3}) & \cdots \\ d(v_{s2},v_{d1}) & d(v_{s2},v_{d2}) & d(v_{s2},v_{d3}) & \cdots \\ d(v_{s3},v_{d1}) & d(v_{s2},v_{d2}) & d(v_{s3},v_{d3}) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \tag{5}$$

where $d(v_{s1}, v_{d1})$ represents the electrical distance between the power source node to the DC line node.

Through depth-first traversal search, the path from each power source to each node of the DC line can be obtained. The process of the depth-first traversal search adopted can be described as: firstly, the power point set and the DC line point set are determined; then takes the element in the power point set as the starting point and the point in the DC line as the end, selects one from the power point set and moves to the adjacent point; if reaches the end, goes back to the previous intersection and chooses another road that has not been taken. As a result, all feasible routes can be searched out by repeating this process.

According to the shortest path principle, the path with the shortest electrical distance is taken from each row in $E(G)$ to obtain the path that connects each power source to the DC line. The obtained interconnection recovery topology therefore takes DC line as the core and connects all available power sources.

In order to make reasonable use of all available sources in the restoration topology, all connectable critical loads can be first incorporated into the restoration topology, where the specific critical loads to be restored will be determined later in Section III. If the "critical load-DC line" path is directly established in this stage, the path may be quite long as the load can be far away from the DC line if the number of nodes in the topology is too large. Therefore, a new topology by combining the formed "power-DC line" path with power sources and DC lines should be established first. Then, by selecting the shortest path of "critical load-new topology", it is possible to avoid the excessive losses caused by long paths that will weaken the restoration performance.

Based on the discussion above, a node matrix of the new topology is established in (6) and (7), which includes all the nodes of the DC lines, connection paths, and power sources.

$$V_{new} = \{V_{source},\ V_{DC},\ V_{connection}\} = \{v_{n1},\ v_{n2},\ v_{n3}, \ldots\} \tag{6}$$

$$V_{loads} = \{v_{l1},\ v_{l2},\ v_{l3}, \ldots\} \tag{7}$$

where the $V_{connection}$ denotes the connection points between the power sources and DC lines.

A complete model with the existing distribution network graph theory model can be formulated, where the electrical distance matrix is established from each load to the new topology as:

$$E(G) = \left[d(V_{loads}, V_{new})\right]. \tag{8}$$

Based on the depth-first traversal search, by searching the shortest path of each row in the matrix, the path that connects the critical load to the new topology can be obtained. According to the shortest path principle, the path with the least number of nodes is selected, which will be used as the path for each critical load in connecting to the new topology.

2) 'Power Sources - Critical Loads' Path Search

Due to the large scale of the actual distribution networks, extreme disasters may cause line faults at multiple locations. As a result, it is not guaranteed that all power sources and critical loads can be connected to a certain DC line. In the case that multiple power sources cannot be interconnected, the search for the critical loads is supposed to start from a single power source. Due to the existence of DC lines, the number of feasible solutions for single power source is usually limited, thus the optimal solution can be obtained by checking the feasible solutions in sequence, where only the solution with highest resilience index will be selected.

Similar to the (3) and (4), the node matrixes of the single power supply and loads which cannot be connected to the DC line are established. The restoration path that directly connects the critical load and the power source is established firstly, i.e., the "power-critical load" path. The node matrix of the power source and the critical load are obtained as (9) and (10), respectively.

$$V_{single\ source} = \{v_{ss1},\ v_{ss2},\ v_{ss3}, \ldots\} \tag{9}$$

$$V_{single\ load} = \{v_{sl1},\ v_{sl2},\ v_{sl3}, \ldots\} \tag{10}$$

A complete model with the existing distribution network graph theory model is formulated. An electrical distance matrix is established from each independent load to the single power source as

$$E(G) = \left[d(V_{single\ source}, V_{single\ load})\right] \tag{11}$$

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Then, the path from the power source to the critical load can be obtained. In this process, multiple feasible topologies can be searched out. Through the verifications of the power sources and the power flow operational constraints in Section III, the feasible recoverable topologies can be searched out. On this basis, the final restoration topology can be determined by comparing amongst the recoverable topologies [20].

In summary, the restoration topology obtained in the topology search stage is divided into two parts. The first part is the multi-power sources and multi-load restoration topology with DC lines as the core. The second part is the single-power source and multi-load AC restoration topology.

However, due to the limited energy of the available power sources in the distribution networks, not all loads can be restored. Therefore, all loads can be regarded as Boolean variables with two states, i.e., recovery and non-recovery. The final restoration topology can be determined together with the real data to formulate a most effective restoration strategy.

III. Post-Disaster Restoration Strategy

A. Resilient Restoration Model

Based on the resilience curve under extreme natural disasters [34]-[37], in the restoration process of the four stages of resilience improvement, the resilience index is often defined as the product of the electrical energy recovered for loads and the loads' weighting factors, which can represent the restoration capability of the system. The resilience of distribution networks can be improved significantly by increasing the power supply F to critical loads with higher priorities, i.e., with larger weighting factors, during the restoration period. Therefore, the restoration strategy of the distribution network proposed in this paper aims at maximizing the power supply F. More specifically, when the total energy of the available power sources in the distribution network is less than demand, the emergency power sources are used to restore the critical loads with the highest priority first. According to this restoration objective, the resilience index used in this paper is expressed as the product of the load weighting factors and the actual amount of power recovered for the loads, as shown in (12).

$$\max F = \sum_{l \in L} \omega_l E_l = \sum_{l \in L} \omega_l P_l t_l \tag{12}$$

where L is the set of critical loads in the distribution network, l is a load in the set L. ω_l is the weighting factor of load l with a higher number indicating a more critical load. E_l is the electrical energy recovered for load l, P_l is the power demand of load l, and t_l is the restoration period for load l.

In the load restoration stage that relies on network resources, it is necessary to coordinate the supply and demand relationship between the source and the load. Since under extreme disaster where the available power supply is less than the demand, all available resources are supposed to be used to their full capacity until the restoration process is complete.

For solar generation, the constraint in (13) is to guarantee the full utilization of the renewable power.

$$P_{pv,t} = \mu_{pv} P_{pv} \tag{13}$$

where $P_{pv,t}$ represents the power generation from the PV panels, μ_{pv} is the power output curve of PV panels, and P_{pv} is the rated power of PV panels.

For diesel generators, the constraint in (14) is to ensure that the amount of fuel used for power generation within n hours will not exceed the total amount of fuel.

$$E_{DG} = \sum_{t \in (1,n)} E_{DG,t} \tag{14}$$

where E_{DG} is the maximum capacity of diesel generation, and $E_{DG,t}$ is the power generation at time t.

For energy storage devices, the constraint in (15) is to ensure the stored energy after n hours is the minimum.

$$E_{LAB,n} = 0 \tag{15}$$

where $E_{LAB,n}$ represents the stored energy after n hours.

The constraints for power flow of AC and DC can be referred to [24] and [25].

According to the recovery topology that incorporates DC interconnections in Section II, different restoration strategies can be used to determine the optimal solution of (12).

For the recovery topology obtained by the topology search method, there are multiple power sources and multiple critical loads with DC lines as the core. In order to maximizing the resilience index in (12), given a fixed amount of total power supply, it is necessary to satisfy and fully restore the critical loads with higher weight as much as possible in the restoration process after a natural disaster. The verifications will be given in next part. According to the order of the weighting factors, there will always be one and only one load that can only be restored partly, while other loads with even lower weighting factors cannot be restored at all.

In descending order of the weighting factors of the load, the loads ranked from 1 to j-1 can be fully restored, of which the actual restored power E_l is equal to the load demand power E_{l0} of the node. The load that ranks j based on its importance can only be partially recovered, of which the actual recovered power E_l is less than the load demand power E_{l0} of the node. E_l is hence the difference between the remaining power of the entire network and the network loss. The loads that rank from j+1 to L cannot be recovered, i.e., the actual recovered power E_l is 0. In summary, the actual power that can be recovered at each node in the distribution system can be expressed as:

$$E_l = \begin{cases} E_l^0 & l \in [1, j-1] \\ E - \sum_{m=1}^{j-1} E_m^0 - \sum_{t=1}^{T} P_t^{loss} & l = j \\ 0 & l \in [j+1, L] \end{cases} \tag{18}$$

where E is the total power of the emergency power supply. P_{tloss} is the total network loss at time t, and T is the duration of the restoration process.

B. Two-Step Optimization Strategy

After the extreme event, the available power sources are usually too limited to fully retore all the critical loads. In order to address this issue, a two-step optimization strategy is proposed in this paper, i.e., the problem in (12) is separated into two stages as shown in (19). *Stage 1* assumes that the total amount of emergency power supply during the restoration period is fixed, then the load restoration strategy is optimized to obtain the load reconnection plan during each period in the restoration process that maximizes the E_w. After the load reconnection plan is determined, *Stage 2* optimizes the real-time output of emergency power supply to reduce the network losses, i.e., minimizes the E_{loss}.

$$\max F = E_w - E_{loss} \tag{19}$$

where E_w is the sum of products of the load restoration energy and their weights, E_{loss} is the sum of energy lose.

As shown in (19), the objective function is influenced by the weighting factor of the critical loads to be restored and the available energy. With the proposed optimization, the loads with a higher weighting factor will be restored first to maximize the objective function. The detailed verification process is shown as follows:

Assume the number of loads to be restored is n. F_1 is the value of the objective function where the loads are restored according to their weighting factors, i.e., the loads in the order of 1 to j-1 can be fully restored. The load that ranks j is partly restored. As a result, F_1 can be expressed as:

$$F_1 = \sum_{l=1}^{j} \omega_l E_l \tag{20}$$

Assume F_2 is any one of the restoration results that have not followed the order of weighting factors of critical loads. Then F_2 can be expressed as:

$$F_2 = \sum_{l=1}^{n} \omega_l E_l' \tag{21}$$

By subtracting F_2 from F_1, the following expression can be obtained:

$$F_1 - F_2 = \sum_{l=1}^{j} \omega_l \left(E_l - E_l'\right) - \sum_{l=n+1}^{n} \omega_l E_l' \tag{22}$$

As ω can be arranged in order, (22) can be re-written as:

$$F_1 - F_2 \geq \omega_j \sum_{l=1}^{j} \left(E_l - E_l'\right) - \sum_{l=j+1}^{n} \omega_l E_l' \tag{23}$$

which can be further expressed by (24) via expanding the contents in the bracket:

$$F_1 - F_2 \geq \omega_j \left(\sum_{l=1}^{j} \left(E_l\right) - \sum_{l=1}^{j\text{-}1} \left(E_l'\right) \right) - \sum_{l=j}^{n} \omega_l E_l' \tag{24}$$

As $\sum_{l=1}^{j}(E_l)$ indicates the total available energy of the system, then (25) can be obtained.

$$F_1 - F_2 \geq \omega_j \left(\sum_{l=j}^{n} \left(E_l'\right) \right) - \sum_{l=j}^{n} \omega_l E_l' \tag{25}$$

As ω is arranged in order indicating that F_1 - F_2 will always be greater than zero, hence it is verified that the proposed *Stage 1* solution can guarantee the maximization of the objective value, where

$$\begin{cases} E_w = \sum_{l=1}^{j\text{-}1} \omega_l E_l^0 + \omega_j \left(E - \sum_{l=1}^{j\text{-}1} E_l^0 \right) \\ E_{loss} = \omega_j \sum_{t=1}^{T} P_t^{\text{loss}} \end{cases} \tag{26}$$

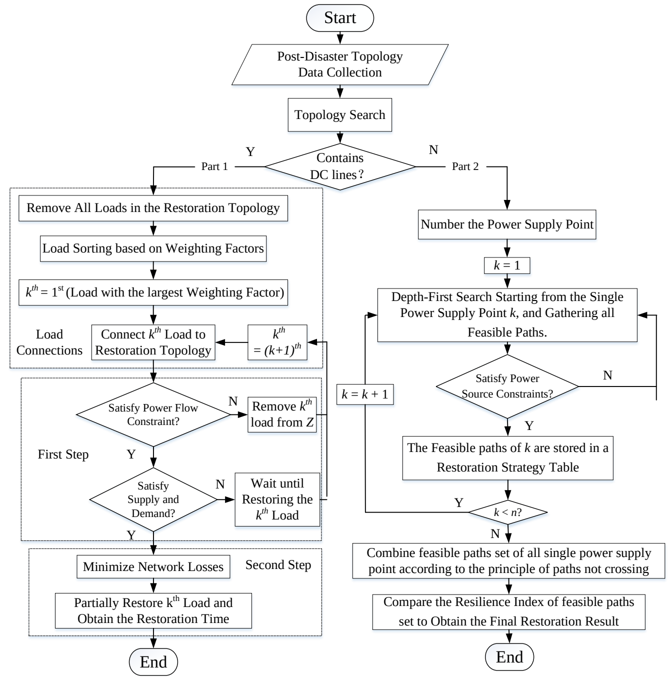

Fig. 3. Flow chart of the proposed two-step load restoration strategy.

From the above mathematical analysis, it can be observed that E_w is a fixed value. In order to obtain the maximized objective function F, the problem is transformed into a grid operation optimization problem, where the objective function is to minimize the grid losses while considering the power flow of the grid as the constraint. In this proposed model, two kinds of losses are included, i.e., line loss and VSC loss.

The operational loss can be calculated as:

$$P_{\text{loss\_VSC}} = \frac{6.62 S_N}{600} + \frac{1.8 V_N^d}{600} \times I_c + \frac{1.98 \left(V_N^d\right)^2}{600 S_N} \times I_c^{\ 2} \tag{27}$$

where the P_{loss_VSC} denotes the VSC loss, S_N denotes the capacity of VSC, V_{Nd} is the voltage of the DC line, I_C denotes the current amplitude.

The optimization variables are the output power of the allocable resources (e.g., PV and energy storage) and the VSC.

Among the existing research on the mixed integer programming (MIP) problem considering the operation of distribution networks, the mixed integer second-order cone programming problem (MISOCP) is a commonly used one. For MISOCP, the original non-linear constraint, which is hard to deal with, can be "relaxed" to a second-order cone-convex constraint that is much easier to be solved.

The relaxation process greatly expands the feasible region. In order to prevent the optimal solution from not satisfying the original nonlinear constraint, the objective function in turn needs to be "tightened" to ensure that the optimal solution exactly satisfies original nonlinear constraints.

The original power flow constraints of distribution networks in (28) and (29) are relaxed by the MISOCP, as shown in (30) and (31), respectively.

$$i_{\text{AC},ij,t} = \frac{P_{\text{AC},ij,t}^2 + Q_{\text{AC},ij,t}^2}{u_{\text{AC},i,t}} \tag{27}$$

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$$i_{\mathrm{DC},ij,t} = \frac{P_{\mathrm{DC},ij,t}^2 + Q_{\mathrm{DC},ij,t}^2}{u_{\mathrm{DC},i,t}} \tag{28}$$

$$P_{\mathrm{AC},ij,t}^2 + Q_{\mathrm{AC},ij,t}^2 \le i_{\mathrm{AC},ij,t} u_{\mathrm{AC},i,t} \tag{29}$$

$$P_{\mathrm{DC},ij,t}^2 + Q_{\mathrm{DC},ij,t}^2 \le i_{\mathrm{DC},ij,t} u_{\mathrm{DC},i,t} \tag{30}$$

where set $u(j)$ is the set of head nodes of the branch with j as the end node in the AC/DC hybrid distribution network. Set $v(j)$ is the set of end nodes of the branch with j as the head nodes. $U^{AC}_{i,t}$ and $U^{AC}_{j,t}$ are the AC voltage amplitudes of node i and node j. $P^{AC}_{ij,t}$ and $Q^{AC}_{ij,t}$ are the three-phase AC active power and AC reactive power at the head of branch ij. $P^{AC}_{j,t}$ and $Q^{AC}_{j,t}$ are the net injection value of AC active power and AC reactive power at node j. $U^{DC}_{i,t}$ and $U^{DC}_{j,t}$ are the DC voltage amplitude of node i and j. $P^{DC}_{ij,t}$ is the head-end DC power for branch ij. $P^{DC}_{j,t}$ is the injected DC power at node j.

To relax the error between $i_{\mathrm{AC},ij,t} u_{\mathrm{AC},i,t} - P_{\mathrm{AC},ij,t}^2 + Q_{\mathrm{AC},ij,t}^2$ and $i_{\mathrm{DC},ij,t} u_{\mathrm{DC},i,t} - P_{\mathrm{DC},ij,t}^2 + Q_{\mathrm{DC},ij,t}^2$ to zero as much, the objective function usually adopts the lowest network loss to "tight", since the network loss is determined by the current flowing through the line. Therefore, the objective function can be considered as minimizing the current for "tightening". When the current reaches the minimum value, the relaxation error approaches zero. It has been proved in [21], [39]-[41] that, the optimal solution of the original optimal power flow problem after relaxation can be guaranteed by using the second-order cone programming method.

As for designing the restoration strategy for topologies with single power source and multiple loads, it is necessary to ensure that the energy of each power source is used completely at the end of the restoration period, i.e., satisfying (14) - (15), then the objective function can be maximized. On this basis, the depth-first search method can be used to obtain multiple feasible paths. By combining the power paths without repeated loads, the objective function values are sequentially compared to determine the optimal restoration plan for topologies with single power source and multiple loads.

The overall flowchart on determining the optimal coordinated restoration method is shown in Fig. 3, which can be divided into two parts.

The first part is by considering the restoration topology with DC link as the core, which contains four steps:

Step 1: All the loads in the restoration topology are disconnected, which are all regarded as the loads to be restored. Then the loads are sorted according to their weighting factors to generate a set Z, which is the set of loads to be restored in the order of 1, 2, 3, …, k, …, n. In this step, the restored load set W is now empty.

Step 2: The load Z_k with the largest weighting factor is connected to the topology for restoration. In this process, the capacity of the distribution network needs to be satisfied. In order to ensure the robustness of results, the verification is made, i.e., after the connection of the k^{th} load, the power flow constraint is tested with the maximum and the minimum output of DGs. If power flow constraint is met, then go to *Step 3*. If fails, remove load Z_k from the load set Z that to be restored, then remove the load Z_k from the restoration topology and return to the beginning of *Step 2*.

Step 3: Verify the supply and demand of the restoration topology. If the total restored energy is greater than the total energy required by load Z_k, then move the load Z_k to the -restored load set W. Z_k is remained in the restoration topology and go back to *Step 2*. If the total energy of the restoration is less than the total energy required by Z_k, then go to *Step 4*.

Step 4: At this time, the total energy distribution of the distribution network is completed. As long as the entire network loss is minimized, the optimal results of the restoration can be achieved.

The second part is to obtain the restoration strategy of the single power supply with multiple loads, which also has four steps:

Step 1: Depth-first search starting from the single power supply point and gathering all feasible power supply paths.

Step 2: Check all feasible paths with the power sources constraints. The feasible power supply paths that meet the requirements are stored in a restoration strategy table. If k is the final power source, go to *Step 3*. Otherwise, repeat *Step 1* and *Step 2*.

Step 3: Integrate all feasible restoration strategy according to the principle of non-duplication of load restoration, and then calculate the objective value.

Step 4: Compare the resilience index of the optimal situation to obtain the final restoration result.

IV. Case Study and Analysis

A. Case Study

In this paper, a distribution network that contains six interconnected lines is used for demonstrating the proposed method, as shown in Fig. 4. The available power supplies after a disaster include diesel generators DG-66, DG-88, DG-125, a PV source PV-110, and a PV-battery energy storage system (BESS) PS-20. Their hourly output power is adjusted within the maximum output power limit. The specific data of various power supply resources can be found in Table I.

As shown in Fig. 4, the lines from node 24 to 44 and from node 44 to 84 are changed to DC lines and reinforced, thus we assume that the DC lines will not be destroyed after an extreme event. In the post-disaster stage, assume that the main power supply has been disconnected, and faults occur on the lines 14-15, 35-36, 131-71.

Based on the proposed topology search method discussed in Section II, the restoration topology can be divided into two parts, as shown in Fig. 5. In the restored topology 2 in Fig. 5, DG-66 cannot connect to the DC line. Hence, only single power supply restoration can be achieved. In the restored topology 1, due to the existence of the DC lines, multiple power supplies can be interconnected to realize the joint recovery amongst various power resources.

With the existence of the DC lines in the topology 1 in Fig. 5, multiple power resources can participate in the restoration process of the distribution network. However, due to the radial operational constraints of the traditional method, only one power supply exists in a single restoration topology, which -

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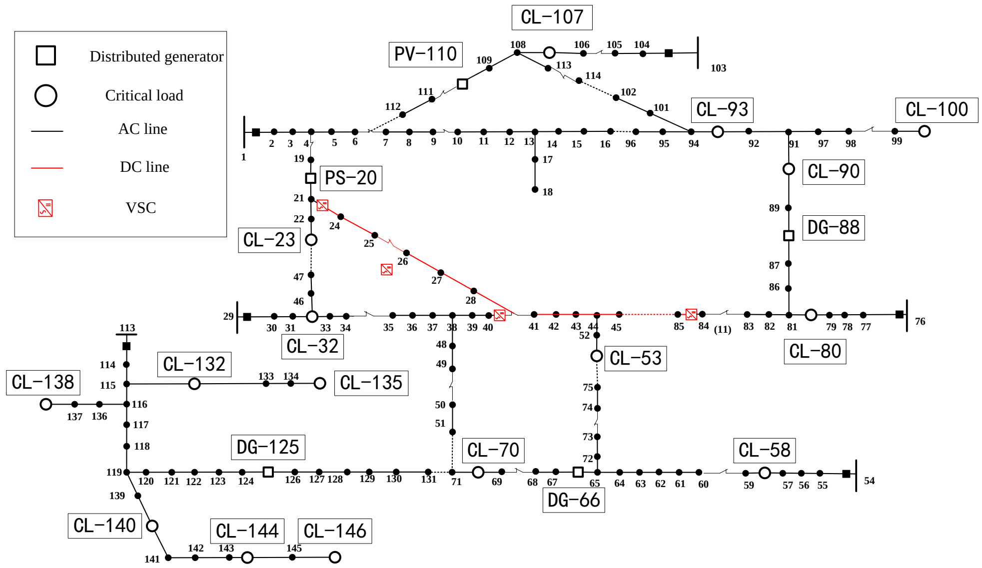

Fig. 4. Distribution network under study.

TABLE I
SUPPLY RESOURCES DATA

Supply resources		Available energy	Maximum power
Controllable supply resources	DG-66	4000 kWh	1000 kW
	DG-88	14000 kWh	1000 kW
	DG-125	3800 kWh	500 kW
	PS-20-BESS	1000 kWh	500 kW
	PS-20-PV	1804 kWh	500 kW
Uncontrollable supply resources	PV-110	902 kWh	200 kW

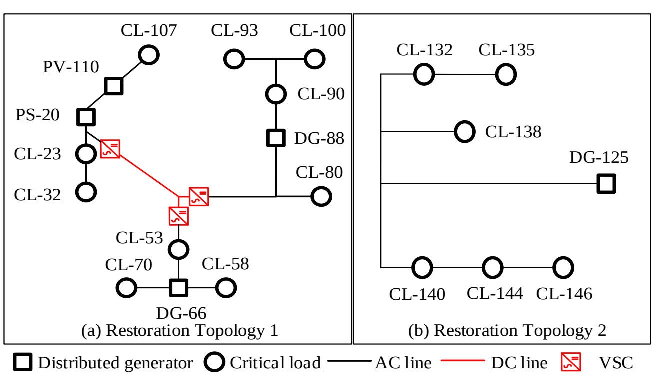

Fig. 5. Restoration topology obtained by the proposed method. (a) Restoration topology 1 with multiple sources. (b) Restoration topology 2 with single source.

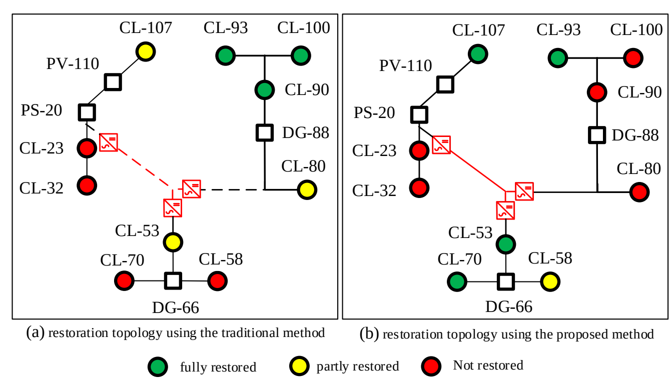

Fig. 6. Results of restoration topology with (a) the traditional AC method with radial constraints and single power supply, (b) the proposed method with multiple power supplies using the interconnections of DC lines.

ignores that the DC line can physically be interconnected. On the other hand, the proposed method fully exploits the capability of the flexible interconnections of DC lines and a topology search method is proposed, which can incorporate multiple power supplies in the same restoration topology for resilience enhancement. The comparisons are as follows.

The single power supply restoration topology using the traditional method and the restoration topology with multiple power supplies using the proposed method are presented in Figs. 6 (a) and (b), respectively. The comparison results of the resilience index and load restoration time are shown in Fig. 7.

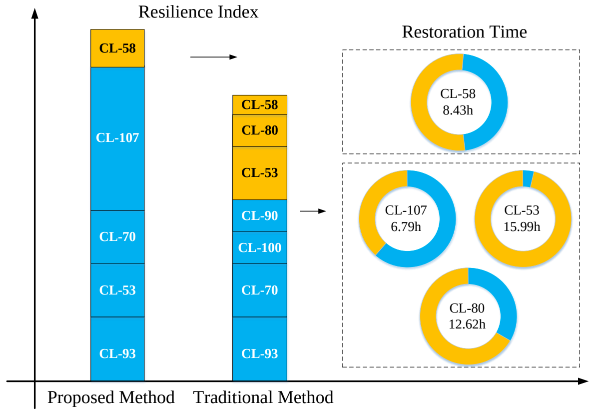

Fig. 7. Comparison results of the resilience index and load restoration time.

With the proposed method, loads CL-93, CL-107, CL-53, CL-70 are fully restored with the total restoration time of 16 h, load CL-58 is partly restored with the restoration time of 8.43 h, while the remaining loads are not restored. With the conventional method, loads CL-93, CL-100, CL-50 are fully restored with the total restoration time of 16 h. Loads CL-107, CL-53, CL-80 are partly restored with the restoration time 6.79 h, 15.99 h and 12.62 h, while other loads are not restored.

Besides, as shown in Fig. 7, the resilience index of the conventional method is 144211.89 kWh, while the one with the proposed method is 182317.07 kWh. Compared with the conventional method, the resilience index has been improved by 26%, since the proposed method fully can utilize the flexible interconnection capability of the hybrid AC/DC distribution network. With the proposed method, all loads to be restored and all the available power supply are connected in one topology, which enables the loads with a higher weighting factor to be restored. On the contrary, the conventional method did not consider this interconnection capability. In the case study, the restoration of the load CL-107 with the second-largest weighting factor is limited by the AC radial operational constraints and can only be connected to a single power supply with PS-20 as the core. The required recovery power within 16 h is 8727.2 kWh. Considering that the total energy of PS-20 and PV-110 is 3706 kWh, therefore, CL-107 can only be partly restored. The load CL-53 with the third-largest weighting factor is restored in a single power supply restoration topology with DG-66 as the core. The total energy required is 4000 kWh, and the total energy of the single power supply is 4000 kWh which will be fully used to restore CL-53. As a result, the loads CL-70 and CL-58 that ranks the fourth and fifth cannot be restored at all. In the single power supply restoration topology with DG-88 as the core, after CL-93 with the highest weighting factor is fully restored. The remaining energy of DG-88 can only be used to restore the CL-100, CL-90 and CL-80, where CL-80 can only be partly restored.

According to the results, the available energy that can be used for restoration with the traditional method is limited. As a result, there always exist one or more loads in the restoration topology that cannot be restored. At the same time, the power supplies with strong capability can only be used to restore the loads with small weighting factors due to the operation constraint. For example, the strongest power supply DG-88 cannot supply power for the high weighting loads such as CL-107, CL-70 and CL-58, which can thus be partly restored. However, it could recover the small weighting loads such as CL-100, CL-90 and CL-80. This uneven distribution of power lowers the resilience index of the distribution network.

On the contrary, the proposed method fully considers the capability of the flexible interconnections brought by the DC lines, where all available energy can be used at the same time. Therefore, the network resilience index can be maximized by load restoration in order according to their weighting factors. In summary, the multi-source and multi-load joint recovery strategy proposed can exploit the advantages of DC lines and greatly improve the resilience of the distribution network.

In the restoration topology 2, as there is only one single power supply, it is only required to recover the important loads with high weighting factors as much as possible to ensure the maximum resilience index. The load restoration result is shown in Fig. 8. As there is no DC line in this case but only a single power supply restoration path, the obtained results are similar to the conventional method.

In Fig. 9, the comparison results of the proposed method with the direct solution through the second-order cone scaling method are presented. As shown in Fig. 9, the proposed method can always obtain feasible solutions in all situations, which cannot be achieved with the second-order cone method. In [22] and [23], a set of sufficient conditions for the establishment of the second-order cone relaxation was derived, where the objective function must be an increasing -

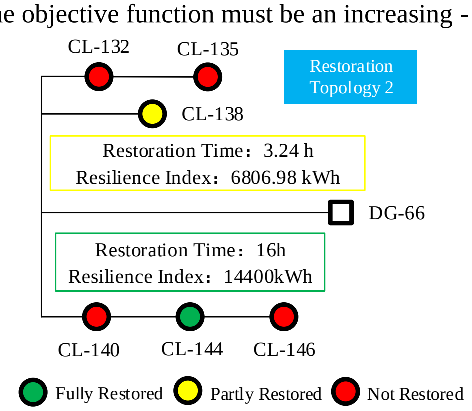

Fig. 8. The results for load restoration by topology search.

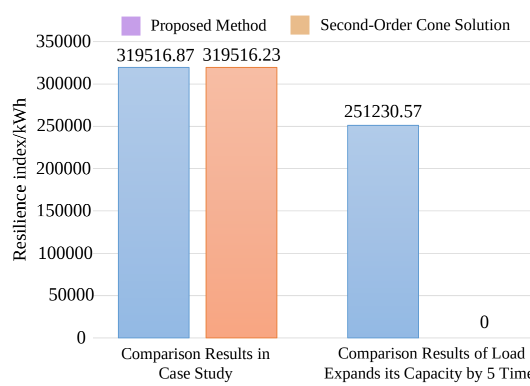

Fig. 9. The comparison results of load restoration using the proposed method and the second-order cone method.

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function of branch currents and the network topology needs to be a tree connected topology. However, considering the case in the paper, the objective function can hardly meet these specific requirements and the network may be looped due to the existence of the DC lines. Therefore, the second-order cone solution method may not obtain a feasible solution, resulting in the zero resilience index.

Consider that the load expands by five times than its original capacity, i.e., the loads exceed the maximum power supply capacity of the line. For the restoration of the load CL-107 with the highest weighting factor, the power must flow over the line 110-107 with 3700 kW, which exceeds the transmission power capacity of the line of 3000 kW. As a result, the constraint (29) cannot be satisfied and feasible solutions cannot be obtained in this case, which results in the zero resilience index. However, with the proposed method that includes a power flow verification process, when the load CL-107 with the highest weighting factor is connected, the CL-107 will not be restored due to the line power capacity limitation. Instead, the load CL-100 with a lower weighting factor is restored. In this case, even though the resilience index is reduced to 250000 kWh, the optimal solution still exists. Therefore, a better applicability is with the proposed method.

On the other hand, as the second-order cone solution is a relaxation method, certain errors will inevitably exist. In the case study, the results obtained by using the second-order cone relaxation are nearly consistent with the proposed method, but

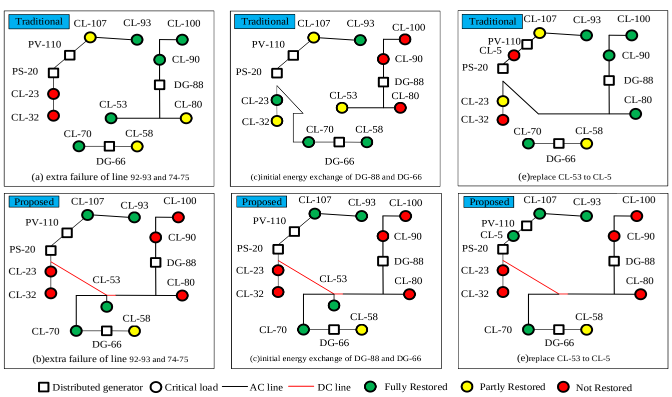

Fig. 10. Load restoration topologies with different disaster severity, resource allocations, and load positions.

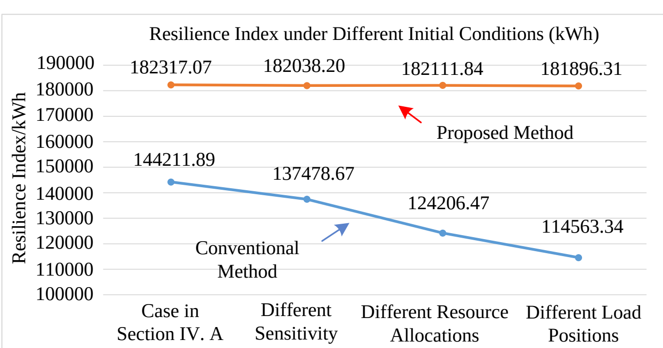

Fig. 11. Comparison results of the resilience index under different initial conditions with the conventional restoration method and proposed method

still with some small errors. Take the load CL-100 as an example. By using the second-order cone method, the recovery time of CL-100 is only 0.0001 h. Such small recovery period is unreasonable under extreme disasters, as it could hardly guarantee the normal power supply of the load, and may even induce greater losses in the instantaneous switching of the loads. By using the proposed method, the physical description of the restoration is more accurate, thus this potential case can be avoided.

B. Adaptability Verifications of the Proposed Method

After an extreme disaster, there are many uncertainties with the initial conditions including the severity of the disaster, the distribution of restoration resources, and the locations of the critical loads. With these uncertainties, it will be proved that the proposed method can always maintain a good restoration effect for various initial conditions, while the restoration effect with conventional method is worse than the proposed method.

To demonstrate the superior adaptability of the proposed method, three initial conditions are used for the restoration topology 1 in Fig. 5, including the different disaster severity, different resource allocations, and different load positions.

The load restoration topologies obtained with different initial conditions are shown in Fig. 10.

(1) *Different Severity of the Disaster*

In this case, it is assumed that the extreme disaster causes failures of additional lines 92-93 and 74-75 in the distribution network, and the remaining initial conditions are the same. After the optimization, the restoration topologies of conventional method and the proposed method are shown in Figs. 11 (a) and (b), respectively. Due to the failure of line 92-93, CL-93 cannot be connected to the single power supply restoration topology with DG-66, but can only be connected to the single power supply recovery topology with PS-20. Due to the failure of line 74-75, CL-53 cannot be connected to the single power supply recovery topology with DG-88, but can only be connected to the one with DG-66. However, with the proposed method, all power sources and loads can still be connected even if the topology has changed.

However, due to the limited energy of PS20, the complete restoration of CL-107 cannot be guaranteed after restoring the critical load CL-93. Besides, as the CL-53 is connected to DG-66 that has a smaller capacity, it cannot be completely restored either, which leads to a decrease in the resilience index.

The resilience index of the conventional method is calculated as 137478.67 kWh, which is 4.67% lower than that in Section IV. A. With the proposed method in this case, the resilience index is 1820387.2 kWh, which is only reduced by -0.15% comparing to the result in Section IV. A. and can be neglected. The main reason for this reduction using the conventional method is that the load with the highest weighting factor CL-93 cannot be supplied by DG-88 due to the line failures, while can only be restored via PS-20 with limited energy.

(2) *Different Resource Allocations*

In this case, it is assumed that the initial energy of DG-66 and DG-88 is different, and other initial conditions are the same with the case in Section IV. A. The initial energy of DG-88 is 4000 kWh, and DG-66 is 14000 kWh. The overall available energy of the system is the same.

After optimization, the restoration topologies of conventional method and the proposed method are shown in Figs. 10 (c) and (d), respectively. In the conventional method, as the restoration capability of DG-88 is weaker than that in Section IV. A. All energy is used to restore CL-53, while loads CL-80, CL-90 and CL-100 cannot be connected to other power sources for restoration. At the same time, DG-66 shows an enhanced restoration capability, since there is still surplus energy after restoring CL-58 and CL-70. Therefore, the remaining energy can be used to restore CL-23 and CL-32. Compared with the results in Section IV. A, the restoration topology of the proposed method does not change, where all power sources and loads are connected to the network and restored in the order according to the load weighting factors.

In summary, the restoration effect of the proposed method is not sensitive to the resource allocations, and the resilience index is almost the same, which proves the better adaptability of the proposed method than the conventional one. For conventional method, if the power supply of the critical loads has a weaker restoration capability, and the available power supply is limited by the radial operation constraints that cannot be connected to the critical loads, the critical loads can hardly be restored. However, loads with small weighting factors are restored instead, which will result in poor restoration effects and the reduction in the overall resilience of the network.

(3) *Different Load Positions*

In this case, load CL-53 is replaced with CL-5 of 250 kW to verify that the proposed method is not sensitive to different load positions. After optimization, the restoration topologies of conventional method and the proposed method are shown in Figs. 10 (e) and (f), respectively. In the conventional method, compared with Section IV. A, CL-53 is lost in the restoration topology formed with DG-88 as the single power supply. CL-100, CL-90 and CL-80 have been fully restored and there is still energy surplus. Therefore, the optimization results show that it is connected to load CL-23 for restoration. Due to the limited energy, the restoration topology formed by PS-20 and-PV-110 can only restore the loads with higher weighting factors as CL-107 and CL-93, but CL-5 cannot be restored. On the other hand, the proposed method can connect all loads and power sources, and the restoration is undertaken in the order according to the load weighting factors, which can ensure a higher resilience index with higher loads restored.

The comparison of the specific resilience indexes under three different initial conditions is summarized in Fig. 11, where the resilience index of the proposed method is always higher than the conventional method. Besides, the resilience index of the proposed method is very stable in different conditions, while the index of conventional method undergoes large fluctuations in different conditions, which further demonstrate the better adaptability of the proposed method.

V. CONCLUSIONS

This paper proposed a load restoration strategy for hybrid AC/DC distribution networks under extreme disasters, which improves the resilience index of AC/DC distribution networks. The conclusions are summarized as follows:

(1) The proposed method could make full use of the flexible interconnections of sources and loads through DC lines. Case study showed that compared with the conventional method, both the restoration time and the amount of load restored with higher weightings are increased. As a result, the resilience index can be improved by 26% through the proposed topology search and coordination restoration method considering DC capability.

(2) The mathematical transformation of the restoration model avoids the situation that a feasible solution cannot be obtained directly in the scenario of limited power supply capacity of the line. Therefore, the proposed method shows a greater applicability.

(3) The adaptability analysis in the case study showed that the proposed method is better than the conventional methods in terms of different disaster severity, resource allocations, and critical load positions, where the resilience index can be increased by 32%, 47% and 59%, respectively.

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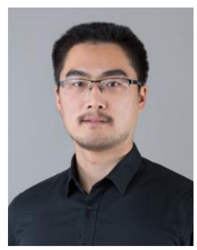

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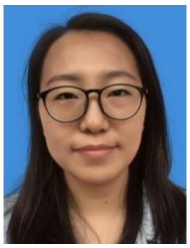

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