A Resilience Enhancement Method for Distribution Networks Based on Preventive-Corrective Coordinated Control

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***Abstract*--To enhance the capability of distribution networks to withstand extreme disasters, a resilience enhancement method based on preventive-corrective coordinated control is proposed in this paper. First, an optimization model integrating preventive and corrective control is established to minimize the control cost, while maximizing the resilience. Furthermore, the Fiedler eigenvalue and corresponding critical edges derived from complex dynamical network theory is introduced to quantify the resilience of the distribution networks and employed as an incentive term to guide the optimization. Before a disaster, the preventive control and corrective control strategies are optimized, with the preventive control strategy being issued first. After disaster occurs, the corrective control strategy is issued as supplement to the preventive control strategy. Finally, case study is conducted on a 42-bus AC/DC hybrid distribution network. The results indicate that the proposed method has a lower control cost and a higher resilience improvement effect compared to other methods.**

***Index Terms*--resilience, distribution network, preventive control, corrective control, Fiedler eigenvalue.**

I. Introduction

With the widespread integration of distributed energy resources (DERs), flexible loads, and emerging energy storage technologies, distribution networks are steadily becoming a key development pathway for future distribution systems [1]. However, the escalating challenge of global warming has triggered worldwide climate anomalies, with extreme events such as typhoons, ice storms, and earthquakes occurring with increasing frequency and intensity [2]. These hazards pose unprecedented threats to the secure and stable operation of distribution networks, which have a high exposure of physical infrastructure. For instance, in 2021, Texas, USA experienced a severe cold wave. The Electric Reliability Council of Texas implemented about 20,000 MW of load shedding to avoid system collapse, and more than 4 million customers faced prolonged outages.

Since extreme disasters often cause structural failures in distribution networks, they can lead to large-scale, long-duration blackouts and significant socioeconomic losses. Therefore, improving the resilience of distribution networks under extreme events is crucial for ensuring secure electricity supply and for building a modern, safe energy system [3].

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Regarding resilience enhancement of distribution networks, both academia and industry have carried out a body of work. Following the evolution of a disaster, the research can be grouped into three stages: pre-disaster, during disaster, and post-disaster resilience enhancement. The pre-disaster stage aims to strengthen the system against potential extreme events. In [4], a quantitative framework for power system resilience from the view of structural vulnerability was built, providing a basis for pre-event investment strategies. In [5], a distribution network resilience planning method based on robust optimization was proposed, which reduces disaster losses through line reinforcement and the deployment of DERS. During a disaster, fast response and maintaining power supply are the top priorities. To improve the emergency response capability of distributed generators, a multi-agent-based method was proposed in [6], which improves the efficiency of network reconfiguration during the disaster. Considering the uncertainty of network damage under extreme events, a robust optimization model that combines network reconfiguration and load shedding was developed in [7], aiming to reduce restoration costs and shorten outage duration. After the disaster, the focus shifts to resource reallocation and optimization of the restoration. The complex network theory was employed to identify critical nodes and guide structural optimization during post-event restoration in [8]. In [9], the distribution network fault recovery problem is coupled with transportation network damage, and a joint repair model was established that enables the restoration of the grid faults and road damages.

Although the above studies provide important theoretical foundations and technical means for enhancing the resilience of distribution networks, there are still certain limitations. First, most existing methods focus on a single stage, resulting in the separation of preventive control and corrective control, which limits the coordination between the two. Second, extreme events primarily cause severe damage to physical components and network topology, yet many works use economic cost as the sole criterion for resilience enhancement, paying insufficient attention to how to improve resilience from the perspective of distribution network structure in different stages.

To this end, a resilience enhancement method for distribution networks based on preventive-corrective

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coordinated control is proposed in this paper. First, a preventive-corrective coordinated control model is formulated, to minimize the preventive control cost and corrective control cost, while maximizing the resilience of the distribution network. Furthermore, the Fiedler eigenvalue and corresponding critical edges derived from complex dynamical network theory is introduced to characterize the resilience of the distribution networks, and it is incorporated into the aforementioned model to guide the optimization. Before a disaster, the preventive control strategy and corrective control strategy are optimized, with the preventive control strategy being issued first. After disaster occurs, the corrective control strategy is issued as the supplement to the preventive control strategy. Finally, the case study is conducted on a 42-bus AC/DC hybrid distribution network modified from the IEEE 33-bus benchmark.

II. Preventive-Corrective Coordinated Control Optimization Model for Distribution Networks.

A. General framework

To enhance the resilience of the distribution networks, a preventive-corrective coordinated control optimization model is developed. The model considers both pre-disaster risk mitigation and fast response during the disaster, and enhances system resilience while satisfying distribution network operational constraints. The general framework is shown in Fig. 1.

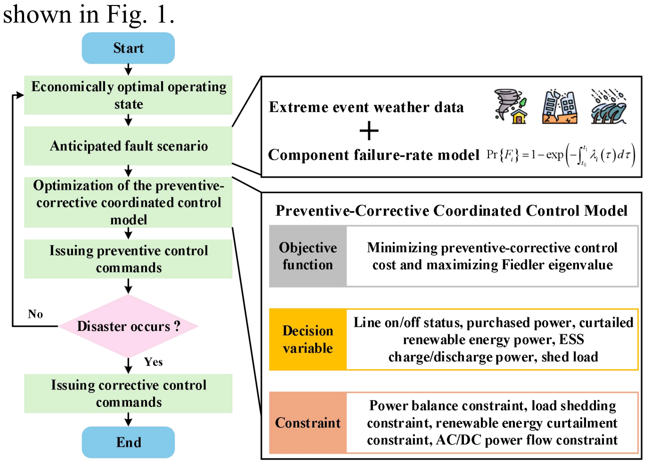

Fig. 1. The general framework of the proposed method.

As shown in Fig. 1, the distribution network operates at the economically optimal operating state under normal conditions. However, to cope with extreme disasters, the distribution network dispatch center needs to adjust the original economic operation plan, and develop reasonable preventive control strategy and corrective control strategy to ensure the safe and stable operation of the distribution network. In the short window before an extreme disaster strikes, weather information can be forecast with reasonable accuracy, therefore, the regional weather data of the distribution networks are combined with component failure-rate models to generate anticipated fault scenario [10]. Under the known fault scenario, the preventive control strategy and corrective control strategy are developed based on the coordinated control optimization model.

The preventive control commands are issued first before the disaster. Then, if the anticipated disaster does not occur, the distribution network returns to economic operation, if it does occur, corrective control commands are issued. This coordinated mechanism of preventive control and corrective control can significantly reduce the intervention intensity of corrective control during the disaster, thereby effectively lowering overall control cost and improving the Fiedler eigenvalue that reflect the resilience of the distribution networks.

B. Objective Function

Traditional preventive or corrective control models mainly minimize economic metrics represented by control cost [11]. However, under extreme events, improving resilience is crucial for secure and stable operation of distribution networks. Therefore, the Fiedler eigenvalue from complex dynamical network theory is introduced into the objective function to reflect the synchronization stability and connectivity of the distribution networks [12]. In addition, the critical edges of the distribution network can be identified based on the Fiedler eigenvalue, which provides guidance for adjustments to the topology, thereby enhancing resilience.

The objective function of the proposed preventive-corrective coordinated control optimization model can be written as:

$$\min\left(C_{\mathrm{pre}} - C_{\mathrm{pre,Fiedler}} + C_{\mathrm{cor}} - C_{\mathrm{cor,Fiedler}}\right) \tag{1}$$

where C_{pre} and $C_{\mathrm{pre,Fiedler}}$ represent the control cost and the Fiedler eigenvalue incentive of the distribution network in the preventive stage, respectively. C_{cor} and $C_{\mathrm{cor,Fiedler}}$ denote the control cost and the Fiedler eigenvalue incentive in the corrective stage, respectively.

1) Control cost in the preventive stage

$$C_{\mathrm{pre}} = \sum_{k \in \left\{\substack{\mathrm{pur,WTC,PVC,} \\ \mathrm{charge,discharge}}\right\}} \alpha_k \left| \boldsymbol{P}_{\mathrm{pre},k} - \boldsymbol{P}_{\mathrm{OPF},k} \right| \tag{2}$$

where $\boldsymbol{P}_{\mathrm{pre},k}$ denotes the optimization variables in the preventive stage, including purchased power, curtailed WT power, curtailed PV power, ESS charging power, and ESS discharging power, $\boldsymbol{P}_{\mathrm{OPF},k}$ represents the optimization variables at the economically optimal operating state of the distribution network, which can be obtained through the optimal power flow (OPF), α_k represents the control cost coefficients of optimization variables in the preventive stage.

2) Fiedler eigenvalue incentive in the preventive stage

$$C_{\mathrm{pre,Fiedler}} = \alpha_{\mathrm{Fiedler}} \lambda_{\mathrm{pre,Fiedler}} \tag{3}$$

where $\alpha_{\mathrm{Fiedler}}$ and $\lambda_{\mathrm{pre,Fiedler}}$ represent the Fiedler eigenvalue incentive coefficient and the Fiedler eigenvalue of the distribution network in the preventive stage, respectively, with its calculation model detailed in [12].

The Fiedler eigenvalue is the second smallest eigenvalue of the Laplacian matrix of the distribution network, representing the synchronous stability of the network. A higher Fiedler eigenvalue indicates that the distribution network has greater stability and resilience under extreme disaster conditions.

3) Control cost in the corrective stage

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$$C_{\text{cor}} = \sum_{k \in \left\{ \substack{\text{pur,WTC,PVC,} \\ \text{charge,discharge}} \right\}} \beta_k \left| \boldsymbol{P}_{\text{cor},k} - \boldsymbol{P}_{\text{pre},k} \right| + \beta_{\text{shed}} \left(\boldsymbol{P}_{\text{shed}} \right) \quad (4)$$

where $\boldsymbol{P}_{\text{cor},k}$ and $\boldsymbol{P}_{\text{shed}}$ are the optimization variables of the corrective stage. $\boldsymbol{P}_{\text{cor},k}$ denotes the purchased power, curtailed WT power, curtailed PV power, ESS charging power, and ESS discharging power in the corrective stage. $\boldsymbol{P}_{\text{shed}}$ represents the shed load in the corrective stage. β_k and β_{shed} represents the control cost coefficients of optimization variables in the corrective stage.

4) Fiedler eigenvalue incentive in the corrective stage

$$C_{\text{cor,Fiedler}} = \beta_{\text{Fiedler}} \lambda_{\text{cor,Fiedler}} \quad (5)$$

where β_{Fiedler} and $\lambda_{\text{cor,Fiedler}}$ represent the Fiedler eigenvalue incentive coefficient and the Fiedler eigenvalue of the distribution network in the corrective stage, respectively.

C. Constraints

1) Switching operation constraint

Frequent switching operations can increase the wear of switching devices and affect the operational reliability of the distribution network. Therefore, a limit on the number of switching operations is imposed, which can be expressed as:

$$0 \le s_\gamma \le S \qquad \gamma \in \{\text{pre, cor}\} \quad (6)$$

where $\gamma \in \{\text{pre, cor}\}$ represents the two states of the preventive stage and the corrective stage. s_γ denotes the number of switching operations in the preventive and corrective stages. S is the maximum allowable number of switching operations.

2) Critical edge constraint

In complex dynamical network theory, the Fiedler vector is the eigenvector associated with the Fiedler eigenvalue. A larger component difference between two adjacent nodes in this vector indicates that the line connecting these nodes contributes more significantly to the Fiedler eigenvalue. Based on this, the lines represented by the node pairs with larger component differences are defined as the critical edges in this paper.

If the lines damaged by a disaster happen to fall on the critical edges, it will reduce the stability and connectivity of the distribution network. To mitigate this risk, the critical edges are restricted to not overlap with the faulted lines, which can be expressed as:

$$0 \le l_{i,\gamma,\text{critical}} + l_{i,\text{fault}} \le 1 \quad (7)$$

where $l_{i,\gamma,\text{critical}}$ is a Boolean variable representing critical edges, where a value of 1 indicates that the line *i-j* is a critical edge, and a value of 0 indicates that the line *i-j* is not a critical edge. $l_{i,\text{fault}}$ is a Boolean variable representing faulted lines, where a value of 1 indicates that line *i-j* is a faulted line, and a value of 0 indicates that line *i-j* is not a faulted line.

3) Load shedding constraint

$$0 \le P_{i,\text{shed}} \le P_{i,\text{load}} \quad (8)$$

$$Q_{i,\text{shed}} = \frac{Q_{i,\text{load}}}{P_{i,\text{load}}} P_{i,\text{shed}} \quad (9)$$

where $P_{i,\text{shed}}$ and $Q_{i,\text{shed}}$ are the active and reactive power of load shedding at node i in the corrective stage, respectively. $P_{i,\text{load}}$ and $Q_{i,\text{load}}$ are the active and reactive power of the load at node i, respectively.

4) Power flow constraint for AC network

Considering that switching operation and extreme disaster can cause topological changes in the distribution network, the Big-M method is employed in this paper to relax power flow constraint, enabling the power flow model to adapt effectively to different topological configurations. The AC power flow constraint can be formulated as:

$$\begin{aligned} M_0\left(\delta_{ij,\gamma} - 1\right) \le V_{i,\gamma}^2 - V_{j,\gamma}^2 - 2\left(R_{ij} P_{ij,\gamma} + X_{ij} Q_{ij,\gamma}\right) \\ + I_{ij,\gamma}^2 \left(R_{ij}^2 + X_{ij}^2\right) \le M_0\left(1 - \delta_{ij,\gamma}\right) \end{aligned} \quad (10)$$

$$P_{ij,\gamma}^2 + Q_{ij,\gamma}^2 = V_{i,\gamma}^2 I_{ij,\gamma}^2 \quad (11)$$

where M_0 is a sufficiently large positive constant. $\delta_{ij,\gamma} \in \{0, 1\}$ is a binary indicator of the line *i-j* status in stage γ (with $\gamma \in \{\text{pre, cor}\}$): 1 if the line is closed, 0 if open. $V_{i,\gamma}$ denotes the voltage at node i in stage γ. $I_{ij,\gamma}$ denotes the branch current on line *i-j* in stage γ. R_{ij} and X_{ij} are the resistance and reactance of line *i-j*, respectively. $P_{ij,\gamma}$ and $Q_{ij,\gamma}$ denote the active and reactive power flows on line line *i-j*, respectively.

For the nonlinear constraint shown in Eq. (11), the second-order cone relaxation method is adopted to transform it into a second-order cone form, which is given as:

$$\left\| \begin{matrix} 2P_{ij,\gamma} \\ 2Q_{ij,\gamma} \\ I_{ij,\gamma}^2 - V_{i,\gamma}^2 \end{matrix} \right\|_2 \le I_{ij,\gamma}^2 + V_{i,\gamma}^2 \quad (12)$$

5) Power flow constraint for DC network

In the DC part of the AC/DC hybrid distribution networks, there is no reactive power component. Therefore, the DC power flow constraint can be written as:

$$\begin{aligned} M_0\left(\delta_{ij,\gamma} - 1\right) \le V_{i,\gamma}^2 - V_{j,\gamma}^2 - 2R_{ij} P_{ij,\gamma} \\ + I_{ij,\gamma}^2 R_{ij}^2 \le M_0\left(1 - \delta_{ij,\gamma}\right) \end{aligned} \quad (13)$$

$$P_{ij,\gamma}^2 = V_{i,\gamma}^2 I_{ij,\gamma}^2 \quad (14)$$

Similar to Eq. (11), Eq. (14) can be converted into the second-order cone form., which is omitted here for brevity.

6) Power balance constraint

$$\begin{aligned} \sum_{j \in \zeta(i)} P_{ij,\gamma} - \sum_{j \in \chi(i)} \left(P_{ij,\gamma} - R_{ji} I_{ji,\gamma}^2\right) + P_{i,\text{load}} + P_{i,\gamma,\text{WTC}} + P_{i,\gamma,\text{PVC}} \\ = P_{i,\gamma,\text{pur}} + P_{i,\text{shed}} + P_{i,\gamma,\text{discharge}} - P_{i,\gamma,\text{charge}} + P_{i,\text{WT}} + P_{i,\text{PV}} \end{aligned} \quad (15)$$

$$\begin{aligned} \sum_{j \in \zeta(i)} Q_{ij,\gamma} - \sum_{j \in \chi(i)} \left(Q_{ij,\gamma} - X_{ji} I_{ji,\gamma}^2\right) + Q_{i,\text{load}} = \\ Q_{i,\text{shed}} + Q_{i,\text{WT}} + Q_{i,\text{PV}} \end{aligned} \quad (16)$$

where $\zeta(i)$ and $\chi(i)$ represent the sets of child nodes and parent nodes of node i, respectively. It should be noted that there is no load shedding term in the preventive stage. Additionally, there is no reactive power balance constraint in the DC part of the distribution network.

7) Other constraints

In the optimization model, node voltages, branch currents, voltage source converters, ESS, and renewable energy curtailment must also meet the corresponding constraints, which are detailed in [13, 14].

III. Case Study

A. Benchmark description

The topology of the 42-bus AC/DC hybrid distribution network is illustrated in Fig. 2. In the distribution network, 8 nodes are integrated with WT rated at 800 kW, 9 nodes are integrated with PV rated at 500 kW, and 2 nodes are integrated with ESS. The capacity of the ESS is 1 MW · h, with a rated power of 500 kW, and the state of charge limits are set at 90% and 10%, respectively. The DER output and the load are shown in Fig. 3.

To simulate the impact of extreme disasters on the distribution network, it is assumed that a typhoon disaster will occur at 15:00, an anticipated fault scenario is generated using the Monte-Carlo sampling and the method mentioned in [10]: lines 9-10, 14-15, and 41-42 will be disrupted by the typhoon at 15:00. These fault are also indicated in Fig. 2.

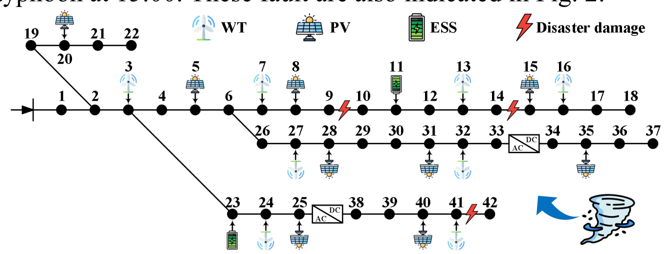

Fig. 2. The topology of the AC/DC hybrid distribution network.

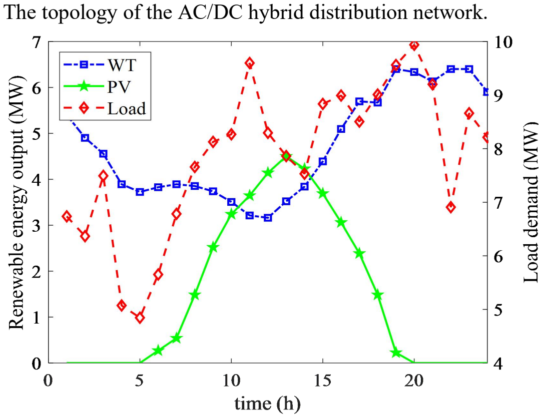

Fig. 3. The DER output and load of the distribution network.

To verify the effectiveness and superiority of the proposed resilience enhancement method, three schemes have been designed for comparative analysis:

Scheme S1: The proposed resilience enhancement method based on preventive-corrective coordinated control.

Scheme S2: In contrast to S1, this scheme does not consider preventive control and only employs corrective control.

Scheme S3: In contrast to S1, this scheme does not incorporate the Fiedler eigenvalue and corresponding critical edges to guide optimization.

The hardware configuration is Intel(R) Core(TM) i5-13500HX CPU. Involved optimization models are formulated on MATLAB R2024a using the YALMIP toolbox and solved with Gurobi 11.0.3.

B. Comparative analysis of simulation results

To verify the advantages of preventive-corrective coordinated control over single corrective control, the comparison between S1 and S2 is first conducted. Fig. 4 and Fig. 5 respectively present the control strategy for the preventive and corrective stages obtained with S1, and the corrective-stage control strategy obtained with S2. The optimization variables of the distribution network under economically optimal operating conditions obtained from the OPF are also shown in Fig. 4 and Fig. 5, to further illustrate the adjustment and control cost of S1 and S2. Table I presents the control costs for S1 and S2, it is noted that the control cost for S1 includes both preventive control and corrective control.

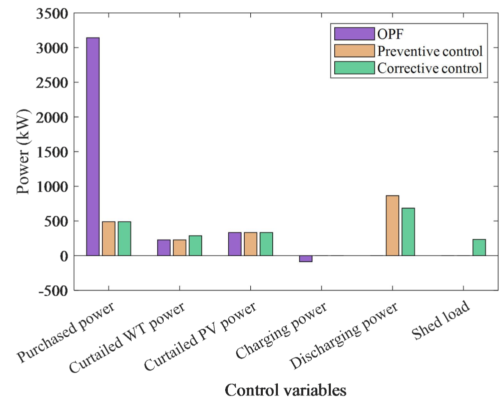

Fig. 4. Control strategy of S1.

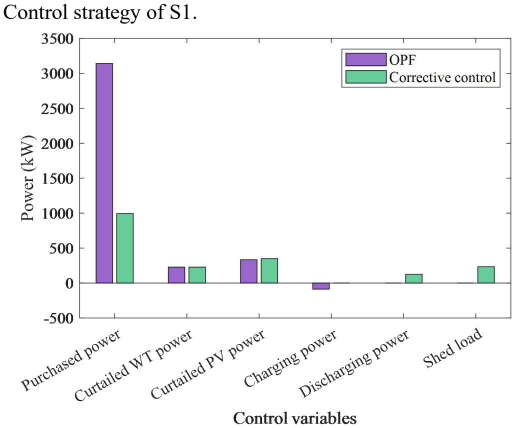

Fig. 5. Control strategy of S2.

TABLE I. Control costs of S1 and S2.

Control costs ($)	S1 (Preventive)	S1 (Corrective)	S2 (Corrective)
Electricity purchasing	530.43	0	1503.99
WT curtailment	0	31.77	0
PV curtailment	0	0	8.22
ESS charging	17.37	0	34.75
ESS discharging	173.04	71.94	50.23
Load shedding	0	937.19	937.19
Total cost	720.84	1040.90	2534.38

From Figs. 4 and 5, it can be seen that S1 reduces the purchased power through preventive control before the disaster and activates ESS in advance to cope with the impending disaster damage. Although this mechanism incurs additional preventive control costs, it alleviates the intensity of corrective control intervention. Moreover, since the unit control cost of corrective control is higher than that of preventive control, S1 still has a lower control cost compared to S2. As shown in Table I, S1 incurs a preventive control

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cost of 720.84$, but its corrective control cost is only 1040.9$, which is a reduction of 1493.48$ compared to the corrective control cost of S2. Additionally, the overall control cost of S1 is only 1761.71$, which is a 30.49% reduction compared to 2534.38$ of S2, thereby verifying the advantage of the proposed preventive-corrective coordinated control method in reducing control costs.

To verify the advantages of introducing the Fiedler eigenvalue to guide the optimization, further comparison between S1 and S3 is conducted. The topology of the benchmark in corrective control stage under S1 and S3 schemes are shown in Figs. 6 and 7, respectively. Since the objective function of S3 does not include the Fiedler eigenvalue incentive term, the objective function values of S1 and S3 are not compared. Instead, the Fiedler eigenvalue and shed load of the two schemes are compared, as reflections of the resilience of the distribution network from the perspective of structure and operation. Table II presents the Fiedler eigenvalue and shed load of S1 and S3 in corrective control stage.

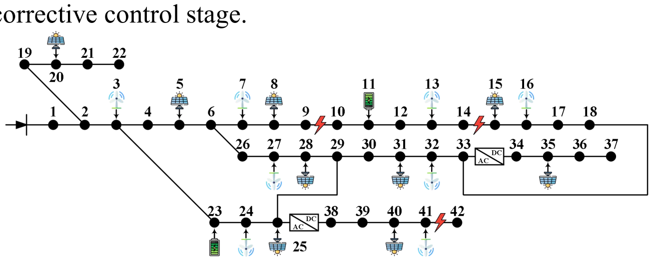

Fig. 6. The topology of S1 in the corrective control stage.

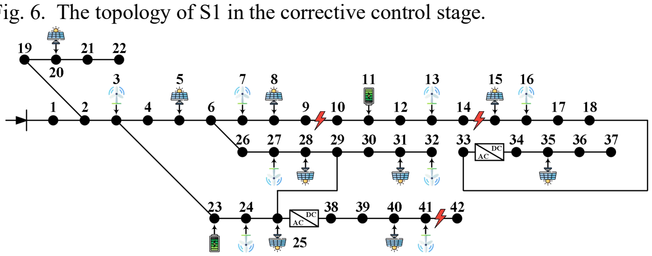

Fig. 7. The topology of S3 in the corrective control stage.

TABLE II. Fiedler eigenvalue and shed load of S1 and S3.

Index	S1	S3
Fiedler eigenvalue	0.0328	0.0297
Shed load (kW)	234.30	247.64

From Figs. 6 and 7, it is observed that both S1 and S3 connect lines 18-33 and 25-29, but S3 further disconnects line 32-33, leading to a reduction in the Fiedler eigenvalue of the distribution network. According to Table II, the Fiedler eigenvalue of S3 is reduced by 9.45% compared to that of S1, indicating a decrease in network resilience and supply capability. Although S3 has formed an island by disconnecting line 32-33, resulting in a lower overall control cost compared to S1, the limited connectivity paths in the distribution network led to more load shedding for S3 by 13.34 kW compared to S1. This result indicates the advantages of the proposed method in enhancing the resilience from the perspective of structure and operation.

IV. Conclusion

To enhance the capability of distribution networks to withstand extreme disasters, a resilience enhancement method based on preventive-corrective coordinated control is proposed in this paper. The results show that the proposed method can reduce the control cost and enhance the resilience of the distribution network.

While this work focuses on pre-event and during-event stages, an important next step is to extend the proposed framework to post-event stage, where the recovery-oriented metrics could be incorporated to more fully characterize resilience across different event stages. Considering the uncertain impacts of extreme events on distribution networks, resilience enhancement under mismatches between anticipated fault scenarios and realized fault scenarios deserves further investigation. In addition, as the framework is applied to larger-scale distribution networks, improving computational efficiency becomes increasingly important. Distributed optimization techniques offer a promising direction to enhance the computational scalability and the real-world applicability of the proposed method.

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