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# A survey on resilient operations of active distribution networks with diversified flexibility resources

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**active distribution networks, cellular architecture, distributed algorithm, flexibility resources, resilience enhancement**

## 1 Introduction

With the widespread utilization of distributed renewable energy and flexible power electronics devices in power distribution networks, the paradigm and characteristics of active distribution networks (ADNs) have undergone profound changes as the traditional radial electricity network will be transformed into multi-layer, multi-ring, AC-DC hybrid networks (Wang et al., 2019). Meanwhile, the unpredictable and intermittent nature of distributed wind and photovoltaic generation poses formidable challenges, hindering the efficient utilization of distributed energy resources (DERs). Furthermore, the renewable-dominated ADNs are usually vulnerable to extreme climate events, such as rainstorm, floods, blizzards and forest fires (Shi et al., 2022; Hua et al., 2023; Cao et al., 2024). Such events generally cause sustained faults of distribution system and renewable energy components, and various renewable energy units with power electronic converters will increase fault currents of distribution networks, resulting in voltage drop, network isolation, or even electricity outages (Khodayar et al., 2014; Ma et al., 2018; Yang et al., 2022). With the increasing penetration level of distributed energy storage (Fang et al., 2023) and electric vehicles (Khatami et al., 2020), the support capability of these flexibility resources can be used for improving the power supply quality and system resilience of active distribution networks. Hence, this investigation aims to offer insightful perspectives and discussions on the resilient operations of ADNs with diversified flexibility resources under extreme events.

The main contributions of this work can be twofold as listed: (1) A cellular architecture of ADNs is presented for renewable energy accommodation and interactive emergency support to enhance multi-microgrid resilience with diversified flexibility resources, and a two-stage resilient model including pre-event preparation and post-disaster restoration is formulated to decrease the load curtailment cost; (2) A multi-level distributed control strategy based on alternating direction method of multipliers (ADMM) is presented to solve the proposed two-stage model of cellular ADNs, thereby autonomous resilient operations and privacy preservation of multi-microgrids can be achieved.

## 2 Cellular architecture of active distribution networks with high renewables

With the growing grid-integration of distributed renewable energies and plug-and-play loads in traditional distribution networks, a series of operational issued are emerged, such as unbalanced three-phase power, voltage sag, transformer overload (Awad et al., 2021; Vijay

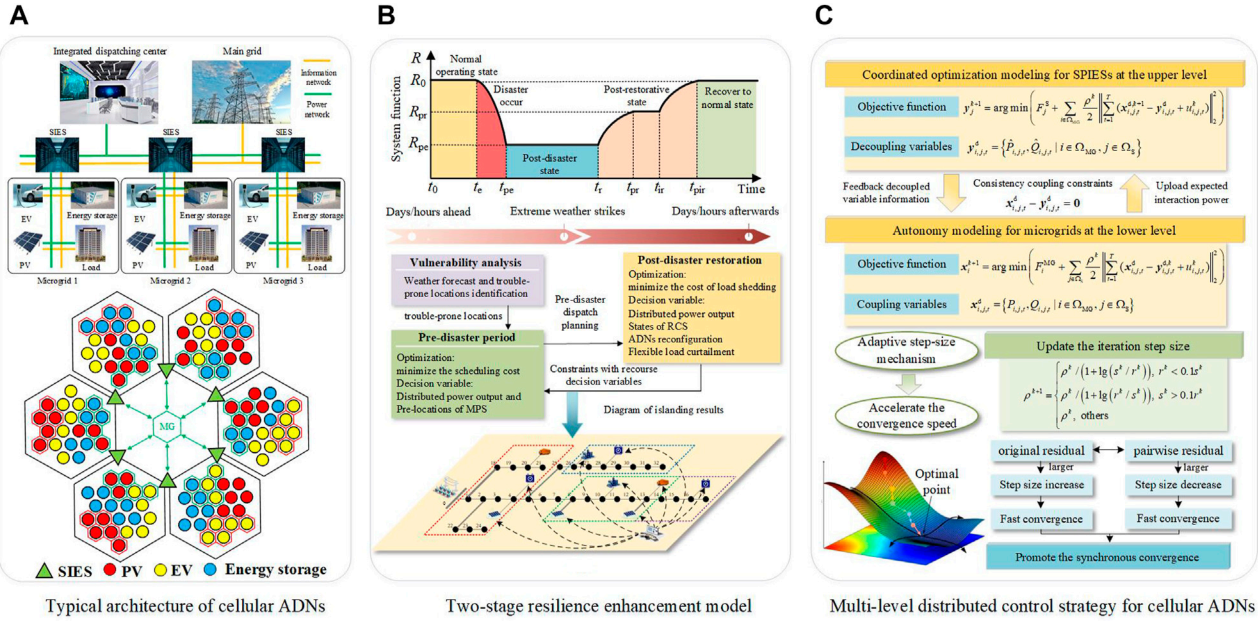



FIGURE 1
The proposed architecture, model and distributed control strategy for cellular ADNs. **(A)** Typical architecture of cellular ADNs **(B)** Two-stage resilience enhancement model **(C)** Multi-level distributed control strategy for cellular ADNs.

et al., 2021). The morphology of "cellular architecture" would be an efficient way to solve these electrical issues of future distribution networks. Cellular architecture of active distribution networks is a set of adjustable hexagonal feeder grids for fine-grained point-to-point power transport control of the ADN system with soft open points (SOPs), and then the economy and reliability of ADN operation can be improved. The unit in the cellular architecture of ADNs is actually an autonomous microgrid system, with high reliability of power supply and integration of flexible renewable energy (Wang et al., 2022).

In the cellular architecture of ADNs, heterogeneous microgrids are interconnected with each other with SOPs and smart information exchange stations (SIESs) (Zhou B. et al., 2021a) to improve the operational flexibility and efficient accommodation of DERs, as shown in Figure 1A. In each microgrid, DERs can be converted and regulated by various converters (Xiao et al., 2023) and storages to mitigate fluctuating renewable generations. The microgrid with surplus renewable energy can directly share with other microgrids, while the microgrid can be injected with energy support from others. Besides, communication techniques among microgrids can be performed by SIESs through the advanced measuring instruments and optical fiber deployed at the engaged sites (Cao et al., 2021). SIESs are designed as interfaces to coordinate the operation of multiple autonomous microgrids with DERs in cellular ADNs, and only informs the dispatch center on the total amount of surplus/deficit energy (Zhou B. et al., 2021a). Though the decentralized structure and coordinated operation, the intermittency and volatility of DERs within cellular ADNs can then be accommodated by diversified flexibility resources such as distributed energy storages and electric vehicles, and then power transmission losses and renewable energy curtailments can be alleviated.

The resilience of ADNs is generally used to assess the system capability for withstanding and recovering from significant energy outages under extreme weather events (Chen et al., 2017a). The resilient operation of cellular ADNs can rapidly disconnect microgrids from the main grid so as to protect power components from upstream disturbances, or to shield voltage sensitive loads from sudden voltage drops (Shi et al., 2022). Under the coordinated control of SIES, SOPs have the potential to island the microgrid from interferences such as failures or power quality incidents. After islanding, the reconnection of microgrids can be performed autonomously during fault recovery phase (Llaria et al., 2011). If the microgrid is partly damaged after a major outage, the SIES will restore energy supply services to emergency and nonemergency loads sequentially using dispatchable DERs such as mobile power sources (MPS) (Li C. et al., 2022a) and energy storages. Cellular ADNs can also be resynchronized with the main grid and shift from island mode to grid-connected mode after extreme events. Therefore, the cellular ADN structure can offer an effective and efficient way to utilize diversified flexibility resources to accommodate renewable energy and enhance system resilience.

## 3 Autonomous resilient operations of distribution networks under extreme climates

Generally, cellular ADNs are vulnerable to extreme climates and then lead to serious power outages and huge economic losses. A conceptual resilience curve related to an extreme weather is shown in Figure 1B to represent pre-disturbance, post-disaster degraded and post-disaster restorative stages for distribution networks (Shi et al., 2022). In this paper, a two-stage resilience dispatch model is proposed to facilitate the pre-disaster prevention and post-disaster recovery of cellular ADNs. In the first stage, MPSs, SIES and SOPs are optimally scheduled to decrease the risk of damage to fault-prone power devices. In the second stage, optimal dispatch of network reconfiguration and flexibility resources is implemented to maintain sufficient and reliable power supplies to critical loads, as shown in Figure 1B.

In the pre-disaster prevention stage, the proposed model aims to dispatch various flexibility resources, including DERs, energy storage systems, MPSs, etc., for minimizing the scheduling cost of diversified flexibility resources and the interaction cost with the main grid. The fault-prone sites are identified based on the fragility model, and MPSs should be proactively pre-located to optimum sites with high potential of failures for survivability enhancement (Wang et al., 2021). DERs should also keep sufficient reserved capacity to cope with voltage fluctuations in the event of power imbalance (Wu et al., 2023). The objective function of pre-disaster preparation model is formulated as Eq. 1 follows,

$$F_1 = \min \sum_{t\in T_1}\left[\sum_{i\in\Omega_{\mathrm{DG}}}\left(C^{\mathrm{DG}}P_{i.t}^{\mathrm{DG}}\right) + \sum_{i\in\Omega_{\mathrm{ESS}}} C_{\mathrm{ESS}}\left(\frac{P_{i,t}^{\mathrm{dc}}}{\eta_i^{\mathrm{dc}}} + \eta_i^{\mathrm{c}}P_{i,t}^{\mathrm{c}}\right)\right. \\ \left. + \sum_{i\in\Omega_{\mathrm{MPS}}}\left(C^{\mathrm{M}}\eta^{\mathrm{M}}P_{i,t}^{\mathrm{M}}\right) + C^{\mathrm{buy}}P_t^{\mathrm{buy}} - C^{\mathrm{sell}}P_t^{\mathrm{sell}}\right]\Delta t_1 \tag{1}$$

where $T_1$ refers to the set of pre-disaster scheduling periods; $\Delta t_1$ is the duration of each pre-disaster scheduling period; $C^{\mathrm{DG}}$, $C^{\mathrm{ESS}}$, $C^{\mathrm{M}}$ represents the cost coefficient of distributed power generation, energy storage operation and MPSs, respectively; $C^{\mathrm{buy}}$ denotes the electricity purchasing cost coefficient of the main grid; $C^{\mathrm{sell}}$ denotes the revenue coefficient from the sale of electricity; $\eta_i^{\mathrm{c}}$, $\eta_i^{\mathrm{dc}}$ is the charging and discharging efficiency of energy storage system, respectively; $\eta^{\mathrm{M}}$ denotes the conversion efficiency between fuel consumption and power output of MPSs; $P_{i.t}^{\mathrm{DG}}$ represents the active power output of distributed energy resources at time period $t$; $P_{i,t}^{\mathrm{c}}$, $P_{i,t}^{\mathrm{dc}}$ denotes the charging and discharging power of energy storage system at time period $t$, respectively; $P_{i,t}^{\mathrm{M}}$ denotes the active power output of fuel-based generator; $P_t^{\mathrm{buy}}$, $P_t^{\mathrm{sell}}$ refers to the purchased active power from the main grid and the sold active power to the main grid at time period $t$, respectively.

In the post-disaster restoration stage, the proposed model is to coordinate network reconfiguration, DERs and repair crew for minimizing the cost of load shedding. The network topology is reconstructed for critical load restoration by dynamically controlling status of sectionalizing and tie switches (Chen et al., 2017b; Shi et al., 2021). Diversified DERs are served as reserved generators to support the power supply within islands for reducing load curtailment (Chen et al., 2023). Moreover, the route and sequence of repair crew is optimized to facilitate the recovery of fault power devices (Arif et al., 2020). The objective function of post-disaster restoration model is presented as Eq. 2,

$$F_2 = \min \sum_{s\in S}\rho_s\left[\sum_{t\in T_2}\left(\sum_{l\in\Omega_{\mathrm{L}}}\left(C^{\mathrm{loss}}w_l P_{l.t.s}^{\mathrm{loss}}\right)\right)\Delta t_2\right] \tag{2}$$

where $T_2$ refers to the set of post-disaster scheduling periods; $\Delta t_2$ is the duration of each post-disaster scheduling period; $\rho_s$ denotes the occurring probability of for scenario $s$; $C^{\mathrm{loss}}$ denotes the penalty coefficient of load shedding and the concrete value is determined on how critical the load is; $w_l$ represents the weight of different loads; $P_{l.t.s}^{\mathrm{loss}}$ denotes the amount of load curtailment at time period $t$.

In order to verify the resilient operation capability of cellular ADNs with the two-stage model, the comparison of per unit of average voltage is shown in Figure 2A. It can be found that per unit of average voltage in cellular ADNs is more stable compared to conventional ADNs.

## 4 Multi-level distributed control strategy for diversified flexibility resources

Considering the individual autonomy and privacy preservation requirements of multi-microgrids in the cellular ADNs, a multi-level distributed control strategy is proposed for solving the two-stage resilient operation model to minimize overall load curtailment cost. At the upper level, SIESs serve as decision-makers to coordinate the energy exchange among multi-microgrids for maintaining power balance. At the lower level, each microgrid achieves autonomous operation through the coordinated scheduling of diversified flexibility resources (Wang et al., 2022). The proposed distributed control problem can be solved by ADMM algorithm, which combines the advantage of decomposability of dual ascent and excellent convergence properties of multiplier method (Rui et al., 2020; Liu et al., 2018). Taking the pre-event preparation model as an example, the resilient optimization problem of cellular ADNs can be decomposed into subproblems for microgrids and SIESs as Eq. 3. The respective optimization objectives are as Eqs 4, 5,

$$\min F_1 = \sum_{i\in\Omega_{\mathrm{S}}} F_i^{\mathrm{S}} + \sum_{i\in\Omega_{\mathrm{MG}}} F_i^{\mathrm{MG}} \tag{3}$$

$$F_i^{\mathrm{S}} = \sum_{t=1}^{T_1}\left(C^{\mathrm{buy}}P_{i,t}^{\mathrm{buy}} - C^{\mathrm{sell}}P_{i,t}^{\mathrm{sell}}\right)\Delta t_1 \tag{4}$$

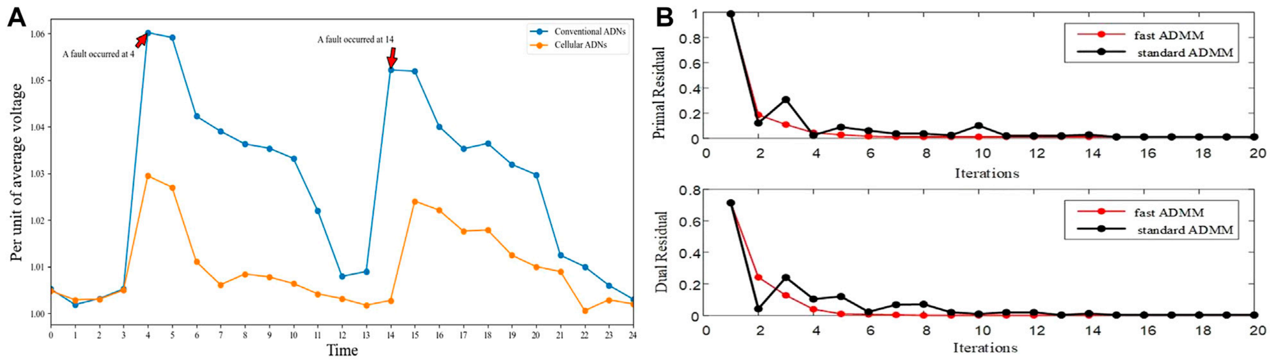
$$F_i^{\mathrm{MG}} = \sum_{t=1}^{T_1}\left(C^{\mathrm{DG}}P_{i,t}^{\mathrm{DG}} + C_{\mathrm{ESS}}\left(\frac{P_{i,t}^{\mathrm{dc}}}{\eta_i^{\mathrm{dc}}} + \eta_i^{\mathrm{c}}P_{i,t}^{\mathrm{c}}\right) + C^{\mathrm{MPS}}\eta^{\mathrm{M}}P_{i,t}^{\mathrm{M}}\right)\Delta t_1 \tag{5}$$

where $\Omega_{\mathrm{MG}}$, $\Omega_{\mathrm{S}}$ denotes the set of microgrids and SIESs; $F_i^{\mathrm{S}}$ and $F_i^{\mathrm{MG}}$ denotes the optimization objective for microgrids and SIESs, respectively.

The optimization variables of hierarchical distributed scheduling strategy for cellular ADNs include diversified flexibility resources regulation power comprised of distributed generation, energy storage and MPSs for microgrids, and the power purchased from or sold to the main grid for SIESs. In addition, the power interaction between interconnected microgrids and SIESs needs to be optimized as coupling variables. Hence, the expected interaction power for microgrid $i$ and SIES $j$ are proposed as coupling variables $\boldsymbol{x}_{i,j,t}^{\mathrm{d}}$ and decoupling variables $\boldsymbol{y}_{i,j,t}^{\mathrm{d}}$, respectively, to establish the consistency coupling constraints as Eq. 6 (Zhou X. et al., 2021b).

$$\begin{cases} \boldsymbol{x}_{i,j,t}^{\mathrm{d}} = \left\{P_{i,j,t}, Q_{i,j,t} \middle| i\in\Omega_{\mathrm{MG}}, j\in\Omega_{\mathrm{S}}\right\} \\ \boldsymbol{y}_{i,j,t}^{\mathrm{d}} = \left\{\hat{P}_{i,j,t}, \hat{Q}_{i,j,t} \middle| i\in\Omega_{\mathrm{MG}}, j\in\Omega_{\mathrm{S}}\right\} \\ \boldsymbol{x}_{i,j,t}^{\mathrm{d}} - \boldsymbol{y}_{i,j,t}^{\mathrm{d}} = \boldsymbol{0} \end{cases} \tag{6}$$

A Lagrange penalty function is added to the objective functions for microgrids and SIESs, as follows,




Comparison of per unit of average voltage between different ADNs

Comparisons of primal residual and dual residual between different ADMM algorithms

FIGURE 2
Comparison between different ADNs and comparisons different ADMM algorithms. **(A)** Comparison of per unit of average voltage between different ADNs **(B)** Comparisons of primal residual and dual residual between different ADMM algorithms.

$$x_i^{k+1} = \arg\min\left(F_i^{\mathrm{MG}} + \sum_{j\in\Omega_{\mathrm{S}}} \frac{\rho^k}{2}\left\|\sum_{t=1}^{T}\left(x_{i,j,t}^{\mathrm{d}} - y_{i,j,t}^{\mathrm{d},k} + u_{i,j,t}^{k}\right)\right\|_2^2\right) \tag{7}$$

$$y_j^{k+1} = \arg\min\left(F_j^{\mathrm{S}} + \sum_{i\in\Omega_{\mathrm{MG}}} \frac{\rho^k}{2}\left\|\sum_{t=1}^{T}\left(x_{i,j,t}^{\mathrm{d},k+1} - y_{i,j,t}^{\mathrm{d}} + u_{i,j,t}^{k}\right)\right\|_2^2\right) \tag{8}$$

where $\rho^k$ is the iteration step size; $u_{i,j,t}^k$ is Lagrange multiplier; $k$ is the number of iterations. The original optimization model is solved iteratively by the above two equations. On the one hand, each microgrid develops a scheduling plan independently with information of internal controllable flexibility resources and uploads the data of expected interaction power $x_i^{k+1}$ to SIESs. On the other hand, each SIES determines the data of $y_j^{k+1}$ and sends it to interconnected microgrids taking into account the needs of power balance and energy interaction. After each iteration, the primal residual $r_k$ and dual residual $s^k$ are calculated as convergence criterion according to Eqs 9, 10.

$$r_k = \sum_{i\in\Omega_{\mathrm{MG}}}\sum_{j\in\Omega_{\mathrm{S}}}\left\|\sum_{t=1}^{T}\left(x_{i,j,t}^{\mathrm{d},k} - y_{i,j,t}^{\mathrm{d},k}\right)\right\|_2 \le \varepsilon_r \tag{9}$$

$$s^k = \sum_{i\in\Omega_{\mathrm{MG}}} \rho\left\|\sum_{t=1}^{T}\left(x_{i,t}^{\mathrm{d},k} - x_{i,t}^{\mathrm{d},k-1}\right)\right\|_2 \le \varepsilon_s \tag{10}$$

where $\varepsilon_r$, $\varepsilon_s$ denotes the convergence threshold for primal residual and dual residual, respectively. If the convergence condition is not satisfied, Lagrange multipliers will be updated according to Eq. 11 and then a next iteration will be proceeded. Otherwise, the iteration is completed to obtain the final scheduling determination of diversified flexibility resources for cellular ADNs, as follows,

$$u_{i,j,t}^{k+1} = u_{i,j,t}^{k} + x_{i,j,t}^{\mathrm{d},k+1} - y_{i,j,t}^{\mathrm{d},k+1} \tag{11}$$

It can be shown from Eqs 7, 8 that both the Lagrange multipliers and iteration step have a dominated influence on convergence properties of the algorithm. The existing conventional method always keeps the iteration step size as a fixed parameter, which restricts the convergence properties owing to the imbalance of primal and dual residuals (Li Z. et al., 2022b; Mhanna et al., 2019). In order to accelerate the convergence speed, an adaptive step-size mechanism can be used to update the iteration step and promote the synchronous convergence of primal and dual residuals as shown in Eq. 12 (Gao et al., 2020; Ghadimi et al., 2015),

$$\rho^{k+1} = \begin{cases} \rho^k/\left(1+\lg\left(s^k/r^k\right)\right), r^k < 0.1s^k \\ \rho^k/\left(1+\lg\left(r^k/s^k\right)\right), s^k > 0.1r^k \\ \rho^k, \text{others} \end{cases} \tag{12}$$

when $s^k$ is larger, the iteration step size $\rho^{k+1}$ increases, accelerating the convergence of $s^k$. Contrarily, when $r^k$ is larger, $\rho^{k+1}$ decreases, preventing the oscillation of objective function and further promoting the local convergence of $r^k$.

The iterative process and acceleration principle of multi-level distributed control strategy for cellular ADNs based on adaptive ADMM algorithm are shown in Figure 1C. Comparisons of primal residuals and dual residuals between different ADMM algorithms are shown in Figure 2B. It can be found that the model convergence speed can be enhanced by 18.7% compared to conventional ADMM algorithms through the adaptive correction of step sizes.

## 5 Discussion and conclusion

A survey on resilient operations of cellular ADNs with flexibility resources under extreme events is presented in this paper. The following are the key findings of this study: 1) The proposed two-stage model utilizes the cellular ADN architecture and diversified flexibility resources to alleviate the damage caused by extreme climate events. 2) A multi-level distributed control strategy based on adaptive ADMM is proposed to solve the two-stage resilient model for the purpose of reducing overall load curtailment cost, and the convergence speed can enhance by 18.7% with the adaptive step-size mechanism. 3) The further research will focus on diversified flexibility resources integration into active distribution networks.

## Author contributions

XL: Conceptualization, Writing–original draft. HZ: Data curation, Formal Analysis, Writing–review and editing. ZL: Visualization, Writing–review and editing. QW: Writing–original draft. HX: Writing–original draft.

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## Conflict of interest

Authors XL, HZ, ZL, QW, and HX were employed by Shenzhen Power Supply Co., Ltd.

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