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Resilient-Oriented Energy Management of Multi-Microgrids Considering Energy Storage and Demand Response Programs Based on a Robust Optimization

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Abstract

The increase in the number and severity of natural disasters and their significant social and economic effects have made power system planners pay special attention to the security and resilience of power networks. This article tries to provide an efficient model for strengthening the resilience of distribution networks based on multi microgrids by optimally using energy storage systems and demand response programs. In the proposed method, a two-stage hierarchical approach has been developed in which the first stage of the incident is modeled. Then, in the next stage, preventive and corrective measures are implemented to increase system readiness and reduce damages caused by severe accidents. In order to consider the uncertainty and the risk caused by it on the proper performance of the proposed design, the problem is done by robust optimization to obtain more realistic results than the deterministic state. Finally, in order to confirm the effectiveness of the proposed method in improving the resilience of distribution systems, a standard network of 33 buses has been used with different operating conditions, and the results indicate its proper performance in the face of severe accidents and maintaining the resilience of the system.

Keywords:

Resilience, Multi-Microgrids, Energy storage systems, Demand response, Distribution networks, Robust optimization.

1. Introduction

In recent years, climate change has significantly increased the frequency and severity of extreme natural disasters worldwide. Power systems are highly vulnerable to such extreme events, as they can lead to widespread infrastructure damage and large-scale outages, emphasizing the critical importance of resilience in modern electrical networks [1]. Although these events are relatively rare, their high-impact nature has attracted considerable research attention aimed at improving grid robustness and recovery capability. Microgrids, equipped with advanced control and protection systems, enable high penetration of distributed renewable energy sources and support coordinated energy management. They also play a key role in maintaining critical loads during emergencies, making them an effective solution for enhancing resilience and system security [2]. In this context, resilience is defined as the ability of a power system to withstand disturbances, respond effectively to disruptive events, and recover rapidly from high-impact, low-probability incidents [3].

Existing studies on microgrid resilience can be grouped into three main categories. The first category includes long-term planning approaches focused on strengthening physical infrastructure, such as optimal system design, distributed generation placement, and mobile energy storage allocation [4, 5]. While effective, these methods are often costly and targeted at critical components. The second category consists of short-term operational strategies designed to prepare systems before disturbances occur. These include energy management of multi-microgrid systems, robust scheduling under grid-connected and islanded modes, and the use of energy storage systems as resilience enhancers [6-8].

The third category focuses on post-disturbance restoration, aiming to rapidly return the system to normal operation through network reconfiguration, load restoration, and optimized repair scheduling [9].

Based on these studies, the main contributions of this paper are:

(i) joint utilization of energy storage systems and demand response programs to enhance distribution system resilience;

(ii) modeling of extreme events and development of a quantitative resilience evaluation index;

(iii) multi-microgrid modeling with consideration of power exchange between interconnected microgrids.:

2. Problem Formulation

The main objective of this study is to develop a comprehensive strategy to enhance the resilience of distribution networks based on multi-microgrid systems against extreme weather events. The proposed framework consists of four sequential stages: (i) defining a quantitative resilience index, (ii) modeling extreme events and their characteristics, (iii) analyzing system response and impact assessment, and (iv) implementing preventive actions to improve system preparedness. Preventive management aims to increase system robustness using available resources such as energy storage systems and demand response programs.

System resilience is defined as the inverse of performance degradation following a disruptive event. In other words, the greater the performance drop after an event, the lower the resilience. The performance loss is quantified by integrating system deviation over time from the event occurrence to full recovery [10]:

$$resilience = \frac{1}{loss} \tag{1}$$

$$loss = \frac{1}{t_4 - t_1}\int_{t_1}^{t_4}\left[\frac{Q_0 - Q(t)}{Q(t)}\right]dt \tag{2}$$

A normalized resilience index is also introduced, where a value of zero indicates a fully resilient system and a value of one represents a completely non-resilient system [11]. System performance can be measured using technical indicators (e.g., frequency, voltage, load shedding, generation availability) or economic metrics.

Extreme weather events are modeled using fragility curves to evaluate equipment vulnerability and failure probability under storm conditions [12]. These models estimate the probability of equipment damage and the number of failed components [13].

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}} ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right] \tag{3}$$

$$P_F = 1 - \prod_{k=1}^{N}\left(1 - P_k\right) \tag{4}$$

Preventive management is especially carried out during the avoidance phase and its main goal is to improve system readiness and mitigate the damage caused by a potential incident, which is achieved by increasing the amount of energy stored in the batteries. Equation (6) shows the amount of energy stored in the batteries that should be maximized so that they can be discharged to the grid at the time of the incident and lead to the supply of a part of the sensitive loads of the grid.

$$\underset{H\&N}{Max}\ F_t^{H\&N} = \sum_{t=1}^{T_c}\left\{\sum_{e=1}^{N_e} SoC_{et}^{ESS}\right\} \tag{5}$$

The studied system includes multiple energy units such as electrical storage systems, fuel cells, natural gas storage, and combined heat and power (CHP) units interconnected within each microgrid. Energy balance equations ensure equality between supply and demand for both electrical and thermal energy. CHP outputs are modeled using gas-to-electricity and gas-to-heat conversion efficiencies. Energy storage systems play a key role in resilience enhancement by shifting energy across time. Their state of charge is modeled dynamically considering charging and discharging power, binary operating states, and operational constraints such as capacity limits and power bounds. Distributed generation units are also constrained by operating regions, ramp-rate limits, and commitment states.

A linearized distribution power flow model is used to efficiently compute active and reactive power flows in radial networks. After a disturbance, power balance constraints, line flow limits, and voltage constraints ensure secure operation within microgrids.

Demand response programs, specifically direct load control, are incorporated to reduce consumption during emergency conditions by adjusting controllable loads. The model enforces equality between increased and reduced demand, ramping limits, and participation constraints to ensure feasibility and operational consistency.

Finally, uncertainty in event timing is handled using robust optimization. The start and end times of disturbances are assumed uncertain within bounded intervals, and a robustness framework is applied to ensure system performance remains acceptable under worst-case scenarios. The approach reduces scenario complexity while guaranteeing a minimum acceptable objective value under uncertainty, with the level of conservativeness controlled by a robustness parameter defined by the system operator.

$$F_w^{base} = \max\ F\left(\mathbf{U}, \xi_t^{srt}\right),\ \forall w \in \{1, 2, ..., N_w\} \tag{6}$$

$$\alpha\left(\mathbf{U}, F_w^T\right) = \max_F \left\{\alpha : \min_{\xi \in \mathbf{U}}\ F\left(\mathbf{U}, \xi_t^{end}\right) \ge F_w^{RA}\right\} \tag{7}$$

$$\forall \alpha \in U\left(\xi_t^{end}, \alpha\right) = \left\{\xi_t^{end} : \left|\frac{\xi_t^{end} - \xi_t^{end}}{\xi_t^{end}}\right| \le \alpha\right\},\ \alpha \ge 0 \tag{8}$$

$$\xi_t^{end}\left(1-\alpha\right) \le \xi_t^{end} \le \left(1+\alpha\right)\xi_t^{end} \tag{9}$$

$$F_w^{RA} = \left(1-\beta^{RA}\right)F_w^{Base} \tag{10}$$

3. Results and Discussion

The proposed framework is tested on the IEEE 33-bus distribution network under several operating conditions. Four scenarios are considered to evaluate the contribution of different resilience enhancement measures:

Case 1: Conventional network without microgrid resources.
Case 2: Multi-microgrid operation with distributed generation units.
Case 3: Case 2 plus energy storage systems.
Case 4: Case 3 plus demand response programs.

Results show that adding storage and demand response significantly improves performance, reduces unserved energy, and speeds up recovery.

Figures 1 and 2 (briefly) show the network structure, post-event microgrid formation, and system response. After the disturbance, the network is divided into microgrids, which enables faster and more flexible restoration.

Overall, the study confirms that combining microgrids, storage, and demand response significantly increases distribution network resilience and reduces outage impacts during extreme events.

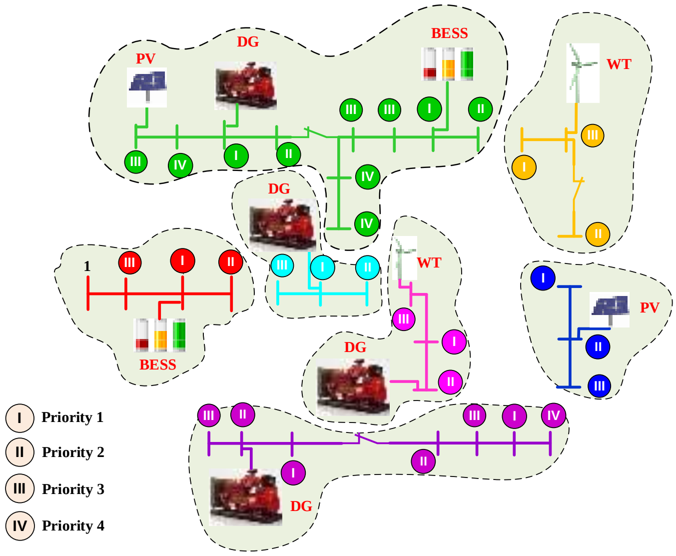

Figure 1. Network structure after the occurrence of the event and the time sequence of load restoration based on their priority.

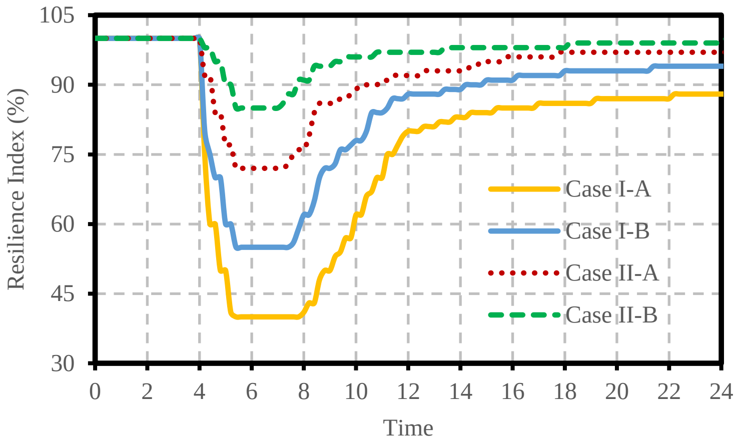

Figure 2. Trapezoidal resilience curve for different cases.

4. Conclusions

This paper proposes a comprehensive approach to improve distribution network resilience under weather events, covering both pre-event (proactive) and during-event (active) stages. Before the event, battery energy storage is charged to increase system preparedness, while during the event, coordinated use of distributed generation, storage, demand response, and microgrids minimizes load shedding. Results show that microgrid partitioning improves resilience by enabling parallel restoration and use of local resources. Energy storage enhances reliability and supports renewable fluctuations, while flexible loads help balance demand and supply. Robust optimization also reduces the impact of uncertainty in renewable generation and event timing, improving overall system performance.

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