Resilience-oriented Operation of Distribution Networks in Presence of Demand Response

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***Abstract*—The resilience of distribution networks is becoming increasingly critical in the face of growing uncertainties and challenges, including climate change impacts, aging infrastructure, and evolving energy consumption patterns. This paper explores the integration of demand response (DR) mechanisms into distribution network operations to enhance resilience. By leveraging DR, distribution networks can dynamically manage energy consumption in response to changing grid conditions and disruptions, thereby mitigating risks and improving system reliability. The paper examines the potential benefits, challenges, and best practices associated with implementing DR in distribution networks to enhance resilience. The insights presented in this paper contribute to the development of effective strategies for enhancing the resilience of distribution networks in the presence of demand response programs. Finally, simulations in the GAMS environment and IEEE 33-bus distribution test network are performed to validate the effectiveness of the proposed strategy.**

***Index Terms*—Resilience, Demand Response Programs, Optimal Operation, Distributed Energy Resources, Smart Grids**

I. INTRODUCTION

The frequency of severe natural and weather-related incidents, such as hurricanes, earthquakes, and floods, has shown a sharp increase. These occurrences have resulted in widespread power outages and significant damage to electrical grids, leading to substantial economic losses and, importantly, extensive blackouts. The concept of ”resilience” has been discussed across different domains, including interconnected infrastructures, national security, and power and energy systems. The Intergovernmental Panel on Climate Change has articulated power system resilience as the ability to anticipate, absorb, and promptly and efficiently recover from adverse events [1].

Typically, the majority of distribution networks are planned and structured with normal weather conditions in mind [2], and there is a need to enhance the resilience of the network against such events. Usually, changing the structure of the current network may enhance its resilience. However, this can be a very costly and time-consuming procedure. Thus, using the existing facilities might be the least expensive solution.

Several proposed solutions aim to address this situation, focusing on optimal energy management and scheduling of the existing units, including distributed generators (DGs) and optimal switching of tie-lines [3]. Demand response (DR) can be considered one of the most efficient and yet least expensive tools in the operation of power networks.

DR refers to alterations in the electricity consumption of end-use customers compared to their usual consumption patterns, driven by some policies and users’ own willingness. Additionally, DR can be characterized as motivations to encourage reduced electricity usage during specific periods according to system requirements [4]. It encompasses any purposeful adjustments made by end-use customers to their electricity consumption patterns, aiming to change the timing, instantaneous demand level, or overall electricity consumption [5].

The incorporation of DR programs (DRPs) has the potential to motivate residential users to reshape their electricity consumption reducing the risk of electricity supply interruptions. Further, this approach also allows to reduce the system interruption during contingencies, and the resilience of the system can be enhanced [6]. Advantages are not limited only to improving the security and technical functioning of the system but there is also a potential for financial benefits for the users.

Optimal usage of DRP can contribute to the more reliable and resilient operation of the power system. DRP operates as a strategic mechanism within distribution networks to manage energy consumption during peak periods or in response to grid instability. By participating in DRP, consumers can adjust their electricity usage in real time based on price signals or grid conditions, thereby supporting grid reliability and stability. DRP typically involves incentives for consumers to curtail or shift their energy usage during times of high de-

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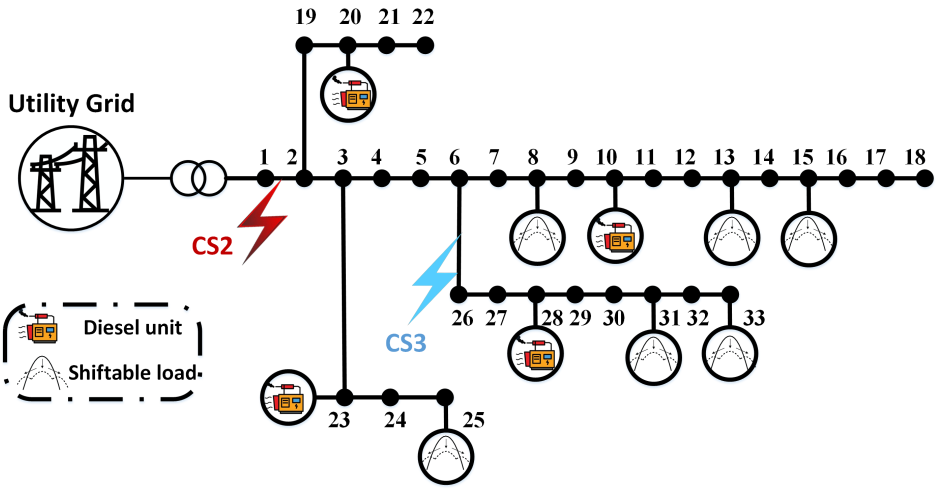

Fig. 1. IEEE 33-bus test network.

mand or supply constraints, such as through load shedding or load shifting practices. This proactive approach helps alleviate stress on the grid, reduces the need for expensive peak generation, and enhances overall grid resilience. Through effective implementation of DRP, distribution networks can optimize resource utilization, improve energy efficiency, and ensure reliable electricity supply during critical periods, ultimately bolstering the resilience of the energy infrastructure [7].

Some researchers have focused on addressing resilience-based scheduling of microgrids. Ref. [8] presents a comprehensive analysis of how microgrids contribute to enhancing the resilience of power systems, exploring topics such as their formation, networked configurations, and resilience in multi-energy networks. The concept of resilience and its various dimensions within distribution networks is explored in [9]. It introduces a novel model based on mixed-integer linear programming to represent and assess the resilience of smart distribution systems effectively. Authors in [10], introduce a resilience-focused optimization approach by incorporating the concept of feasible islanding during regular operation and ensuring the survival of essential loads in emergency situations. Home-Ortiz *et al.* [11] outline a restoration method aimed at enhancing the resilience of electric distribution systems through the utilization of multiple operational resources, including mobile generation units and responsive loads. Likewise, ref. [12] introduces a two-stage approach for restoring critical loads following an extreme event. It involves coordinating distributed generations, microgrids, and demand response programs to manage the restoration process effectively. The authors in [13] illustrate the substantial enhancement of distribution system restoration achievable through the utilization of the flexibility offered by incorporating responsive demands. They put forth a framework that integrates the control of flexible appliances at the household level, aiming to adjust the load demand at the distribution grid level. A risk-constrained stochastic framework is introduced in [14], which is designed for the joint scheduling of energy and reserves in a resilient microgrid, incorporating demand-side management. The optimization problem is structured to manage the system's operation in both normal and islanding modes, while addressing uncertainties such as the duration of islanding and prediction errors related to loads, renewable power generation, and electricity prices. Ref. [15] describes the creation of a resilience-focused optimization model for microgrids featuring hybrid energy storage systems, which is verified through numerical simulations.

Enhancing the resilience of a power system involves minimizing interruptions to loads during contingencies or disruptions. Resilience in this context refers to the system's ability to withstand and recover from various disturbances, such as equipment failures, natural disasters, or cyberattacks, while still providing reliable power to consumers. The goal is to maintain continuity of service and minimize the impact on customers even in challenging circumstances. Accordingly, in this paper, demands are divided into two main groups: The first group involves those who are not participating in demand response programs, and they should be supplied without any interruptions during the normal and contingency conditions. The second group is composed of customers with demand-side flexibility, which can shift their power in various time slots. The distribution network operator (DNO) is responsible for the secure and resilient operation of its network while minimizing its operational costs. This model of enhancing resilience has not been addressed in the literature before.

The rest of the paper is organized as follows: In the second section, problem formulation for optimal resilience-oriented operation of distribution networks is presented. The third section contains simulations and discussions. The final section includes the summary of the paper and conclusions.

II. PROBLEM FORMULATION

Improving the resilience of a power system entails reducing disruptions to loads during emergencies or disturbances. Resilience here denotes the system's capacity to endure and bounce back from different disruptions, such as equipment malfunctions, natural calamities, or cybernetic threats, while still delivering dependable power to users. The objective is to sustain service continuity and diminish the impact on consumers even in case of unwanted events. The demands are subcategorized into two main groups, including DRP groups and non-DRP loads. It is the responsibility of the DNO to ensure the secure and resilient operation of its network while maximizing its benefits.

The problem formulations are shown in terms of Eqs. (1) - (21):

$$Max \quad O.F. = \sum_{t=1}^{t_{final}} \Big[\pi_t \cdot P_t^{grid} - \pi_t \cdot \sum_{k \in \Omega_{dg}} P_{k,t}^{dg} \tag{1}$$

$$+ \pi'_t \cdot \sum_{k \notin \Omega_{drp}} P_{k,t}^{l} - \pi'_t \cdot \sum_{k \in \Omega_{drp}} P_{k,t}^{l} - \pi_t \cdot \sum r_{ij} i_{ij,t}^2 - Res_t \Big]$$

subject to:

$$P_t^{grid} = P_{sell,t}^{grid} - P_{buy,t}^{grid} \quad \forall t \tag{2}$$

$$-P_{max}^{grid} \le P_t^{grid} \le P_{max}^{grid} \quad \forall t \tag{3}$$

$$0 \le P_{k,t}^{dg} \le P_{max,t}^{dg} \quad \forall t, \forall k \in \Omega_{dg} \tag{4}$$

$$P_{k,t}^{l} = P_{k,t}^{l,base} - P_{k,t}^{sh} \quad \forall t, \forall k \notin \Omega_{drp} \tag{5}$$

$$P_{k,t}^{l} = P_{k,t}^{drp} \quad \forall t, \forall k \in \Omega_{drp} \tag{6}$$

$$P_{k,t}^{drp} = P_{k,t}^{drp,base} - P_{k,t}^{drp,down} + P_{k,t}^{drp,up} \quad \forall t, \forall k \in \Omega_{drp} \tag{7}$$

$$\sum_t P_{k,t}^{drp,down} = \sum_t P_{k,t}^{drp,up} \quad \forall k \in \Omega_{drp} \tag{8}$$

$$P_t^{grid} + \sum_{dg} P_{k,t}^{dg} \ge \sum P_{k,t}^{l} \quad \forall t \tag{9}$$

$$Res_t = \sum_{k \notin \Omega_{drp}} VOLL \cdot P_{k,t}^{sh} \quad \forall t \tag{10}$$

$$S_{k,t}^{net} = S_{k,t}^{l} - S_{k,t}^{dg} \quad \forall t, k \tag{11}$$

$$S_{k,t}^{net} = P_{k,t}^{net} + j \cdot Q_{k,t}^{net} \quad \forall t, k \tag{12}$$

$$P_{k,t}^{net} = P_{ik,t} - r_{ik} i_{ik,t}^2 - \sum P_{kj,t} \quad \forall t, k, i, j \tag{13}$$

$$Q_{k,t}^{net} = Q_{ik,t} - x_{ik} i_{ik,t}^2 - \sum Q_{kj,t} \quad \forall t, k, i, j \tag{14}$$

$$v_{k,t}^2 = v_{i,t}^2(t) - 2(r_{ik} P_{ik,t} + x_{ik} Q_{ik,t}) + (r_{ik}^2 + x_{ik}^2) \cdot i_{ik,t}^2 \quad \forall t, k, i \tag{15}$$

$$v_i^{min} \le v_{i,t} \le v_i^{max} \quad \forall t, i \tag{16}$$

$$S_{ik,t}^2 \ge P_{ik,t}^2 + Q_{ik,t}^2 \quad \forall t, k, i \tag{17}$$

$$i_{ik,t}^2 = \frac{S_{ik,t}^2}{v_{i,t}^2} \quad \forall t, k, i \tag{18}$$

$$-\nu_{ik,t} \cdot i_{ik}^{max} \le i_{ik,t} \le \nu_{ik,t} \cdot i_{ik}^{max} \quad \forall t, k, i \tag{19}$$

$$-\nu_{ik,t} \cdot P_{ik}^{max} \le P_{ik,t} \le \nu_{ik,t} \cdot P_{ik}^{max} \quad \forall t, k, i \tag{20}$$

$$-\nu_{ik,t} \cdot Q_{ik}^{max} \le Q_{ik,t} \le \nu_{ik,t} \cdot Q_{ik}^{max} \quad \forall t, k, i \tag{21}$$

Eq. (1) shows the objective function, which comprises six terms. The first term represents power transactions between the distribution network and the utility grid. The second term represents the energy acquired from local generators within the distribution network. The third term represents the power supplied to the non-responsive loads in the network. The fourth term shows the power purchased by the DRP loads. The fifth term indicates the active power loss, which is to be minimized. Finally, the sixth term represents the fulfillment of the resilience objective in network operation.

Eq. (2) shows the power transactions with the utility grid. Positive values for this indicate buying, and negative values indicate selling power to the upstream network. Also, this transactions are limited via Eq. (3).

The maximum amount of purchasable power from local generators within the distribution network is depicted by Eq. (4). This maximum power is assumed to be offered by the generator owner for the day-ahead horizon.

Eqs. (5)-(8) illustrate the demanded power at each bus, whether it belongs to a subset of DRP or represents a fixed load. The total amount of increment in power should be equal to the total amount of decreased power in DRP loads, i.e., if a device is disconnected in a specific period, it should be supplied in another period.

Maintaining equilibrium between energy production and utilization on an hourly basis is crucial in power systems, as shown in Eq. (9).

Eq. (10) expresses the resilience of the network concerning affected non-flexible loads during a contingency. Here, Res represents the cost penalty for load shedding. Resilience is defined for critical loads that do not participate in DRP and require uninterrupted supply. Thus, in a resilient network, the shedding of these loads during contingencies and high-impact events should be minimal.

Distribution systems typically exhibit radial network structures, where the initial bus is connected to the utility grid and possesses a flexible power injection with a voltage of 1 per unit (p.u.).

The convex power flow formulation for such networks is detailed in Equations (11) through (21). Eq. (11) characterizes the net apparent power emerging from each bus, calculated as the difference between generation and consumption. Meanwhile, Equations (12) to (15) establish power flow constraints for determining bus voltages, employing Kirchhoff's laws. The final equations encompass limitations on voltage, current, active power, and reactive power for both buses and lines. The binary parameter $\nu_{ik,t}$ is assigned a value of 1 in normal operating conditions and 0 during contingency events.

In the above formulations, P_t^{grid}, P_t^{dg}, P_t^{l}, and P_t^{sh} stand for active power transactions with upper grid, local generator power, demand power, and shedded fixed load power, respectively. π_t and π'_t show the electricity price in the utility network and the electricity price in the distribution network. π'_t is slightly higher than π_t to provide an arbitrage for the DNO. For instance, in Oulun Energia, for customers with fuses over $3 \times 63A$, the service fee in addition to the electricity price from Nordpool is 2.27 $cents/kWh$ with 0% value added tax [16]. $P_{ik,t}$, $Q_{ik,t}$, and $S_{ik,t}$ are symbols for active, reactive, and apparent power passing through line connecting

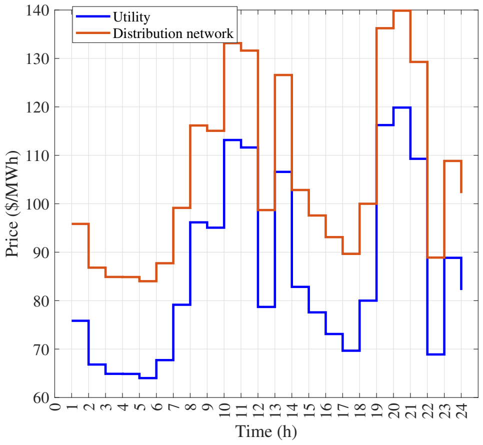

Fig. 2. Electricity price in the day-ahead market.

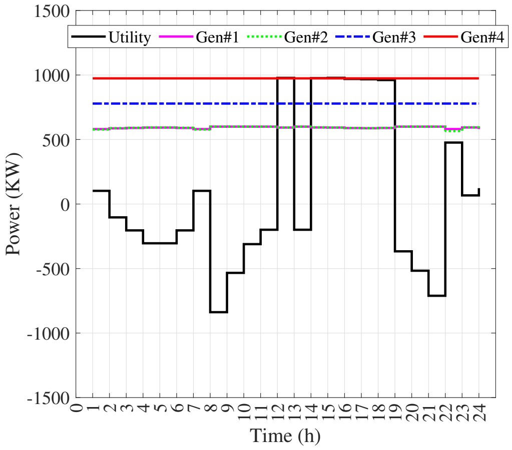

Fig. 3. Power transactions with utility and local generators in **CS1**.

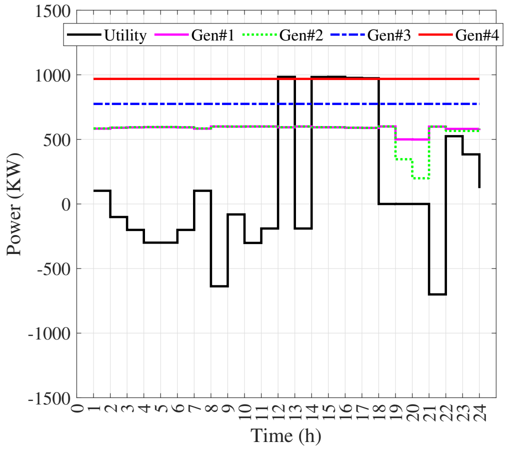

Fig. 4. Power transactions with utility and local generators in **CS2**.

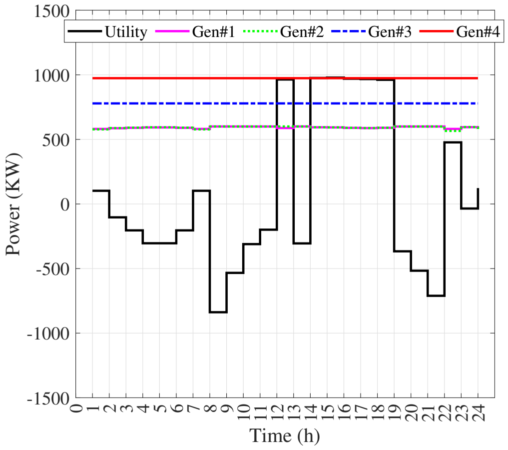

Fig. 5. Power transactions with utility and local generators in **CS3**.

buses i and k. r_{ik} and x_{ik} show the line parameters between buses i and k and finally, $i_{ik,t}$ and v_i indicate the current on line ik and voltage at bus i.

The optimization process is done in a way that, in normal conditions, the DRP loads are satisfied with gaining benefits. In case of emergency and contingencies in the lines of the distribution network, the process is done in a way that the resilience of the network is enhanced via preventing load shedding for the fixed loads, and the shortage of power in the system is compensated by reducing the DRP load levels. In the next section, case studies with simulations will be presented.

III. Simulations and Discussions

This section contains the simulations for testing the effectiveness of the proposed methodology. Simulations are conducted on the IEEE 33-bus test system, and the problem is solved using GAMS software with the CPLEX solver on a system equipped with a Core i5 CPU and 8 gigabytes of RAM under Windows 11 Enterprise OS. The optimization is done for the day-ahead horizon and 1-hour time resolution. Figure 1 illustrates the locations of the various units within the IEEE 33-bus distribution system, including generators and responsive loads, which are assumed to be shiftable loads. Day-ahead electricity price during the energy management period is depicted in Figure 2, which is obtained from the Nordpool price in Finland. The characteristics of units in the system are shown in Table I, and the maximum tradable power with the utility grid is 1000 KW. Voltage variations are allowed between 0.9 and 1.1 p.u., with the voltage of the first bus set at 1 p.u. Three case studies (CSs) are considered as follows:

TABLE I
Generation Units Characteristics

Bus #	P_min (KW)	S_max (KVA)	Q_max (KVAr)
10	25	600	150
20	0	1000	300
23	0	800	300
28	100	600	200

- **CS1**: In this case, it is assumed that the system is working in normal conditions and there is no contingency in the lines of the system.
- **CS2**: In this case, it is assumed that the network has seen an incident and, accordingly, is operated in islanded mode from the utility grid between hours 18 to 21.
- **CS3**: In this case, it is assumed that the system faces an emergency situation between hours 12 to 14 with a contingency in the line connecting buses 6 and 26.

A. *CS1:*

This case is designed to see the normal operation of the network without any contingencies. The system is operating

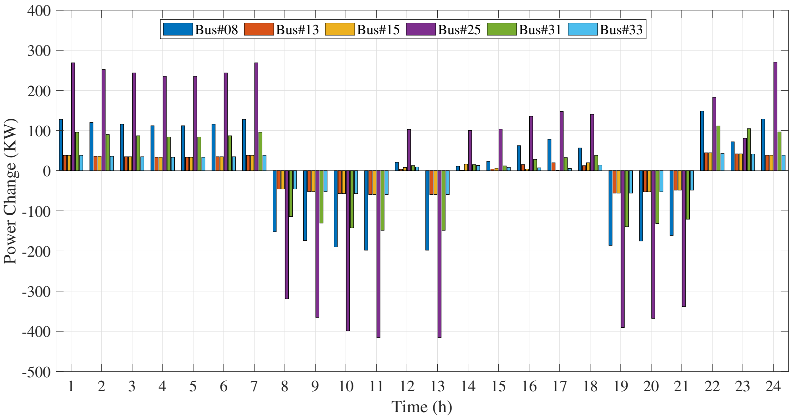

Fig. 6. Power change of demands participating in DR in **CS1**.

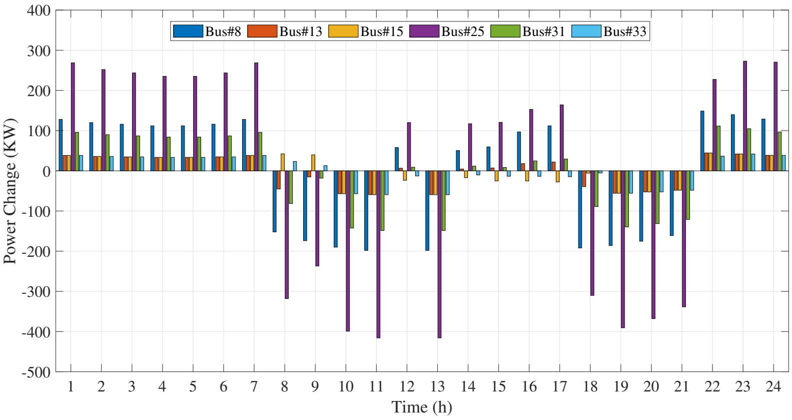

Fig. 7. Power change of demands participating in DR in **CS2**.

in normal conditions and there is no contingency in the lines of the system. The objective function in this case is 2211.74 $. Figure 3 shows the output of the generators and power transactions with the utility grid in the scheduling period. When the price is low, the maximum amount of power has been bought from the utility grid. Figure 6 demonstrates the up/down amount of power for the flexible loads participating in the DRP. In the high price period, we see a rise up, and in lower price times, we see an increase.

B. CS2

In this case, it is assumed that the network faces a contingency in the line connecting buses 1 to 2, and the system is operating in an islanded mode between hours 18 to 21. Figures 4 and 7 show the local generation power, utility transactions, and also power changes in the DRP loads, respectively. The value of the objective function is 2178.321 $. As it can be seen, between hours 18-21, the power transactions with the utility is zero. Also, there is a noticeable decrease in the power of the DRP loads during contingency hours. Although the system works in islanded mode for three hours, by optimally using local sources and performing DRP efficiently, the load shedding in the system is zero.

C. CS3

In this case, it is assumed that there is a line cutting between buses 6 and 26, and the section from bus #26 to #33 is isolated from the system between hours 12-14. Figures 5 and 8 illustrate the power generation and up/down power changes in the flexible loads. The value of the objective function is 2136.06 $. Between hours 12 to 14, the power reduction in the buses #31 and #33 is significant. For instance, at hour 12, other flexible loads have seen an increment in their power due to the lower price period, but loads connected to buses #31 and #33 have seen a decrease to avoid load shedding for the non-flexible loads. The reason for objective function decrement compared to **CS2** is performing this DRP in non-optimal periods in terms of electricity price, however to enhance the resilience of the system in unwanted events, this more price is inevitable.

IV. CONCLUSION

In this paper, we tried to use optimal DRP in distribution networks to enhance the resilience of the system in case of contingencies in the network. Through the utilization of DRP, distribution networks can flexibly regulate energy usage to adapt to fluctuating grid conditions and disturbances, thus reducing risks and enhancing system resilience. The findings presented here aid in crafting efficient approaches to fortify distribution networks against disruptions, particularly through demand response initiatives. The distribution network operator is not only responsible for optimal energy management but also performs a convex load flow to ensure the system is operating within its security limits. The shiftable loads are assumed to be in the system as flexible loads, and by utilizing

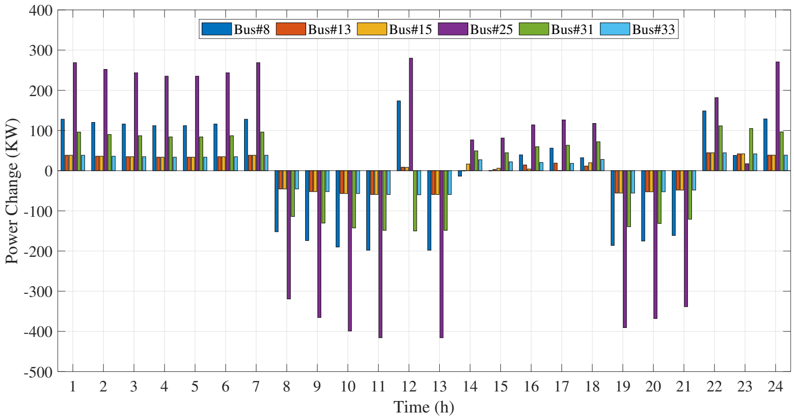

Fig. 8. Power change of demands participating in DR in **CS3**.

the controllability of these sources, the network operator might be capable of enhancing system resilience in case of contingencies. The simulations conducted in the GAMS environment and using the IEEE 33-bus distribution test network validate the efficacy of the proposed strategy. Three case studies have been employed, including normal operation, contingency in lines connecting buses #1 and #2, and also buses #6 and #26. No load interruption has been seen during the optimization period. For the future work, it is planned to use AI/ML algorithms to be used in the optimization process whether in prediction models or in computation method using edge, fog or cloud computing.

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