Enhancing resilience of the smart urban electrical and gas grids considering reserve scheduling and pre-event responses via the onsite supply strategy of the energy storage systems and demand response

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Research Article

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Abstract: Due to climate change and the occurrence of natural disasters in recent decades, energy supply to consumers has faced risks in different areas, especially in urban areas. Hurricanes are the most common natural disasters in urban areas in the damage to energy grids like electrical distribution grids. This study focused on enhancing resilience oriented in the electrical distribution grids in urban areas with smart grid technologies. The poles outage by hurricanes in the electrical distribution grid is introduced as a natural event subject to scenario generation via the pole fragility function. The short-term reserve scheduling is proposed as a pre-event response for enhancing resilience oriented against event at day-ahead. The reserve scheduling is implemented with attention to three strategies such as installing backup generators (BGs), demand response program (DRP), and storage systems (SSs) utilization considering microgrids formation in the damaged areas. The BGs are fed by urban gas grids for supply electrical demand in the damaged areas. In following, DRP is considered for demand management based on offer prices to consumers for demand reduction. Also, the SSs are operated by consumers as onsite generation for meet self-demand in the during event. The implementation of the proposed approach is done by using tri-objectives such as 1) minimizing the reserve costs, 2) minimizing the consumers' dissatisfaction, and 3) maximizing the resilience oriented of the electrical distribution grid. The GAMS software and augmented ε-constraint method are presented for solving reserve scheduling. Finally, the superiority of the pre-event responses considering proposed reserve scheduling is verified via numerical simulation on the IEEE 33-bus distribution grid in the several case studies.

Key words: Resilience oriented; Smart grid; Pre-event response; Short-term reserve scheduling; Demand response program (DRP); Tri-objectives.

Nomenclature

Indices and Sets

t, T	Time indices
bg, BG	Backup generators (BGs) indices
ss, SS	Storage systems indices
i, m	Microgrid indices
s, S	Scenarios indices
p	Poles index
rc, RC	Residential consumers indices
cc, CC	Commercial consumers indices
ic, IC	Industrial consumers indices
a, b	Buses indices

Parameters

v_{cr}, v_{ine}	Critical wind speed and wind speed with inevitable probability in the pole outage state, respectively.
MG	Number of microgrids
N_{BG}	Number of Backup generators (BGs)
N_{SS}	Number of Storage systems (SSs)
$\zeta_{RC}, \zeta_{CC}, \zeta_{IC}$	Bid prices for DRP in residential, commercial, and industrial consumers, respectively.
$\lambda_{SS}, \lambda_{gas}$	Operation price of SSs and gas price, respectively.
D_{eq}	Total electrical demand in microgrids
G_{GAS}^{D}	Gas demand in microgrids

$\eta_{ss}^{DCH}, \eta_{ss}^{CH}$	Efficiency of SSs in discharge and charge modes, respectively.

Decision variables

f_1, f_2, f_3	Objective functions including reserve cost, consumers' dissatisfaction and resilience index, respectively.
C_{BG}, C_{SS}	Reserve costs of the BGs and SSs, respectively.
C_{RC}, C_{CC}, C_{IC}	Reserve costs for implementing DRP by residential, commercial and industrial consumers, respectively.
$D_{RC}^{DRP}, D_{CC}^{DRP}, D_{IC}^{DRP}$	Value of the reduced electrical demand in DRP by residential, commercial and industrial consumers, respectively.
v, f_{poles}^{hw}	Wind speed and failure probability of poles in wind speed *v*, respectively.
PS, pt	Poles status and tolerance threshold of the poles, respectively.
$P_{SS}^{CH}, P_{SS}^{DCH}$	Charging and discharging powers of SSs, respectively.
P_{BG}, Q_{BG}	Active and reactive powers of BGs, respectively.
G_{GAS}	Gas generation by gas grid
D_{nsd}	Non-supplied demand
V_a	Voltage of bus *a*
$P_{a,b}$	Power flow between buses *a* and *b*
E_{SS}	Energy available of SS
$\pi(s)$	Probability of the poles in the scenarios
κ	Binary variable of the Non-supplied demand
u_{ss}	Binary variable of SS. 1=discharging mode and 0=otherwise

1. Introduction

1.1. Aims and Background

Due to the existence of fundamental consumers such as industrial, commercial, and residential; meeting energy demand with maximum reliability in urban areas is a vital issue for energy organizations [1][2]. The urban areas have sensitive and important energy infrastructure for supplying energy demand with high population density [3]. Hence, non-supplying energy to the demand side can lead to develop consumers' dissatisfaction and social challenges in the urban areas [4][5]. Electrical energy has a major contribution in supplying demand for the industrial, commercial, and residential sections in urban areas by electrical distribution grids. Also, most equipment and devices in the industrial, commercial, and residential sections are supplied via electrical energy; and lack of the meeting demand or blackout can increase harmful effects on the demand side [6]. Generally, the blackouts of the electrical distribution grids are created by three factors such as natural events, intentional factors by humans, and technical problems. Regarding, the published report of the Energy Department in the USA, blackouts caused by natural events and weather disasters in recent years are expanding [7][8]. The most common weather disaster is occurrence of the hurricanes in urban areas with destructive effects on the electrical distribution grids. On the other side, solutions are introduced in recent investigations against weather disasters like hurricanes under namely resilience-oriented enhancement [9][10]. The concept of resilience-oriented enhancement in energy systems such as electrical distribution grids is defined as decreasing weather disasters' effects with low probability and high impact. Actually, resilience-oriented enhancement can be implemented in three modes including 1) Pre-event responses, 2) During event responses, and 3) Post event responses [11][12]. Also, implementation of these modes has time scales considering duly responses for resilience-oriented enhancement [12][13]. The modes of resilience-oriented enhancement with time scales are depicted in Fig.1. Actually, Pre-event responses are preventive strategies based on scheduling for resilience-oriented enhancement; and Post event responses are restoration strategies after the event [12][13]. The functions of these modes for resilience-oriented enhancement may be varied considering energy system topologies. In urban areas, there are multiple energy like electrical and gas for resilience enhancement with attention to future natural disasters [14]. Also, the abilities of the smart grid technologies can adaptive in urban areas by considering the linkage between generation and demand sides via telecommunication infrastructure [15]. The integration of the smart grids in the urban energy grids has optimal impacts on the technical and economic indices towards resilience-oriented enhancement during events [16]. These abilities of the smart grids' technologies include demand response programs (DRPs), Real-time awareness of consumption, and adaption of the system with existing conditions. Also, distributed energy resources (DERs) such as backup generators (BGs) and storage systems (SSs) can be used in urban areas for resilience-oriented enhancement via meeting demand in the damaged areas. These opportunities in the electrical distribution grids can be implemented by reserve strategies based-Pre event responses towards increasing the capacity of the electrical grids and resilience-oriented enhancement [16][17].

In Fig.2. the Background of the proposed electrical distribution grid integrated with the gas grid and smart grid in urban area is shown. In this figure, local operators with attention to forecasting the status of the electrical distribution grid and identification of vulnerable areas will be coordinated with the central operator for installing BGs, SSs and implementing DRPs before the event. The BGs are fed by urban gas and SSs are installed for meeting demand during the event. The BGs are installed in the damaged poles in the electrical distribution grid via microgrids formation. The SSs are operated by consumers in the damaged areas or microgrids as an onsite supply strategy, and installation of the SSs in the residential sections with high population density and consumption is considered. As well, DRP is carried out based on various bid prices to industrial, commercial, and residential sections for demand reduction during the event. Accordingly, these strategies can implement as reserve energy scheduling for resilience-oriented enhancement at day-ahead and during event.

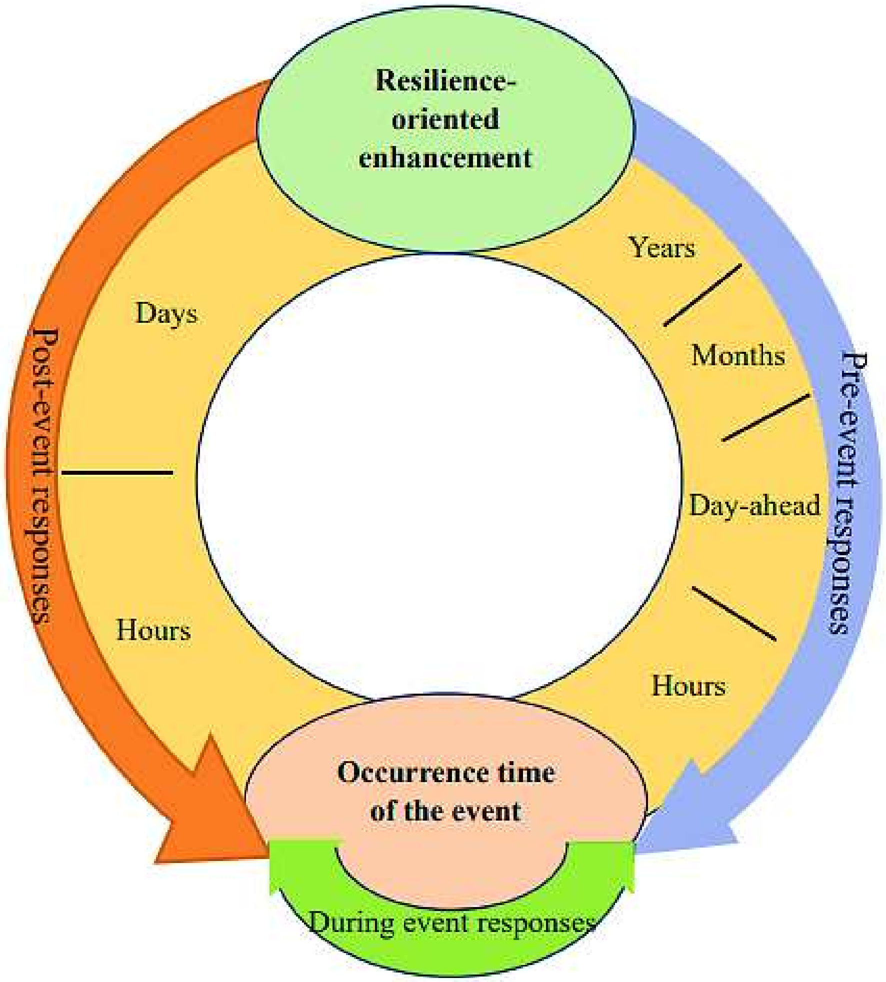


Fig.1. Modes of the resilience enhancement [12].

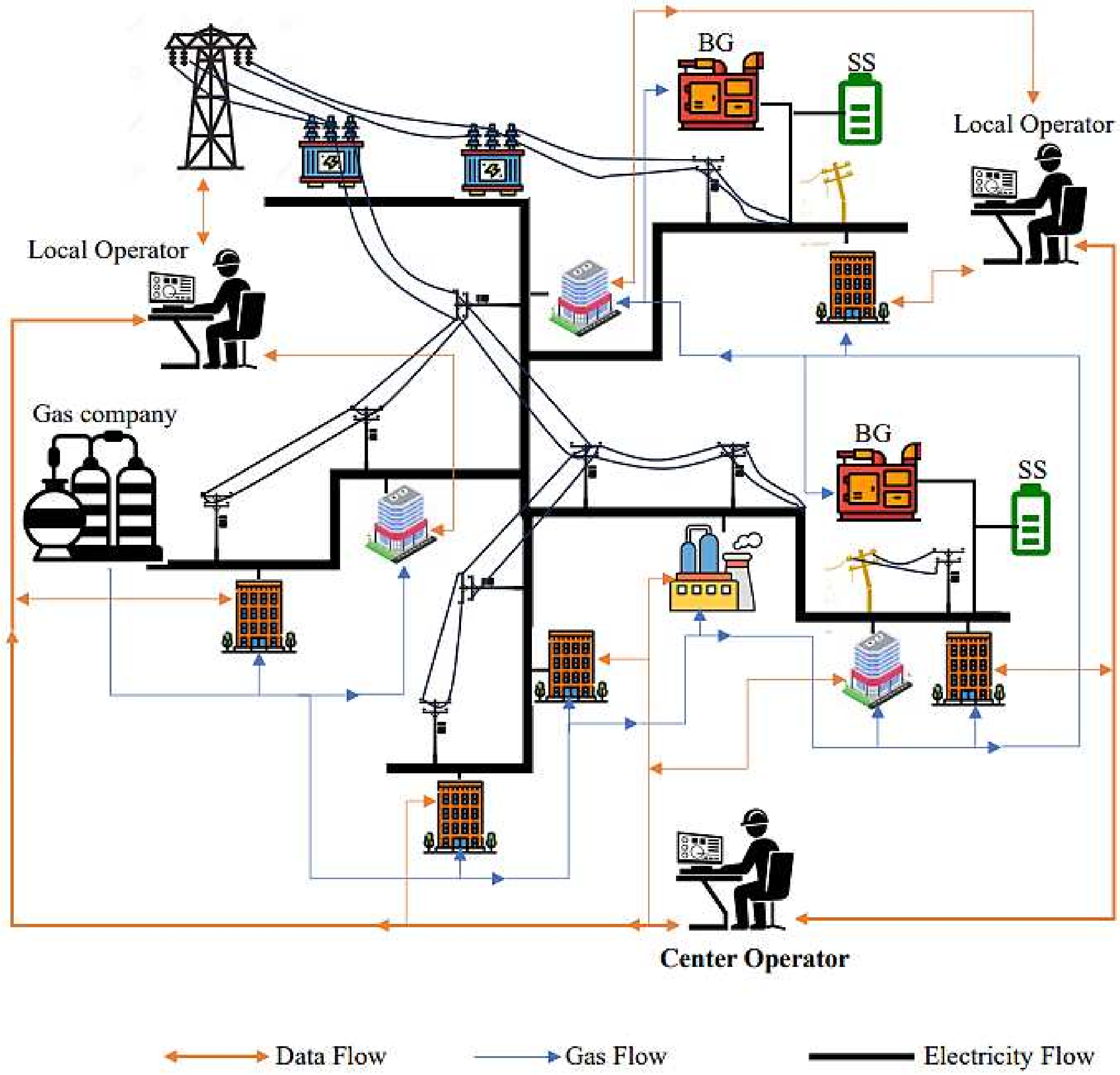


Fig.2. Background of the proposed electrical distribution grid in urban area.

1.2. Related Studies

The recent studies on the resilience enhancement in the energy systems with various topologies and strategies is investigated in this subsection. In [18] a tri-level optimization model considering network reconfiguration of the integrated electricity and heat system is proposed for resilience enhancement under risk-averse scheduling. In [19] long-term resilience enhancement based-investment planning for the electrical distribution grids with consideration of the lines hardening and lines underground placement is proposed. In [20] optimal allocation of electric vehicle (EV) charging stations in New York City is investigated for improving equitable resilience of urban energy grids by machine learning and data-driven approaches. Also, in [21] optimal charging and discharging schedules of the EVs in the electrical grids for minimizing the load shedding and resilience enhancement by using distributed control strategy is studied. The distributionally robust programming is proposed in [22] for resilience enhancement in the distribution and transmission electrical grids using unmanned aerial vehicle and mobile SSs. The coalitional game and graph theories based-reconfiguration strategy is implemented in [23] for reducing the expected load curtailment and lines outage during extreme events. The resilience scheduling of the multi-agent multi-energy systems with participation of the mobile EVs in meeting energy demand under stochastic nature of the renewable energy resources and EVs is reported in [24]. In [25] mobile energy hubs are introduced for maximizing restoration of critical loads and reducing restoration time span in the electrical distribution grids with shortest path algorithm. A resilience quantification framework based on real-time power outage in the demand side is proposed in [26] considering tie-lines implementation and reconfiguration of the electrical distribution grids in the post-event. In [27] bi-layer robust optimization framework with hydrogen storage system and optimal switching in the distribution grids is studied for increasing resilience index in the island mode. A multi-stage recovery process for improving resilience by using progressive hedging algorithm in the restoration stage and coordination of the multiple energy resources is presented in [28]. In [29] Distribution feeder reconfiguration of the distribution grid by bi-level optimization is modeled for minimizing the forced load shedding using multiple SSs. The long-term optimization framework as two-stage modeling is proposed in [30] for recovering rapidly from disruptive events via optimal design of the energy resources based on economic index. In [31] optimal placement of the SSs in the distribution grid for the reduction of the curtailed priority loads in Urmia city in Iran under extreme winds is studied. In [32] model predictive control is presented for power allocation optimization and voltage control in DC microgrids by using hybrid energy SSs against various disturbances. In [33] investment planning based- risk averse index is considered for transmission lines resilience with attention to placement of the wind farms, static VAR compensators and installing gas pipelines. In [34] complex network theory is proposed for withstand capability of the electrical distribution grid under extreme events for optimal planning and operational resilience using solar panels installing. The resilience planning based on two-phase framework of the capacity accessibility and cascading effects by events is discussed in [35] via bi-directional energies conversion. The resilience enhancement by using offshore-island renewable distribution systems and optimal sizing and siting of the SSs is presented in [36]. The restoration responses for mixed cascading failures of the electrical distribution grid via hardening and the number of hired maintenance crews after events by joint optimization approach are studied in [37]. The underground cables, EVs participation and clustering of distribution grids for resilience enhancement against earthquakes by techno-economic strategies are considered in [38]. In [39] resilience assessment considering multi-type natural disasters in the urban areas in Taiwan is studied based on long-term resilient planning and planning costs. In [40] energy resources sizing and reconfiguration approach against potential cyberattacks in the smart distribution grids is implemented for resilience enhancement in the islanding mode. The brief comparison of the mentioned studies with our work is assessment in the Table.1.

Table.1. A comparison of the mentioned studies with our work.

Ref	**Enhancing resilience using**			**Approach of resilience enhancement**	**Type of Enhancing resilience**	**Time scale of Enhancing resilience**	**Objectives**		
	BG	**SS**	**DRP**	**Reserve scheduling**	**Pre-event**	**Day-ahead**	**Reserve cost**	**Consumers' dissatisfaction**	**Resilience index**
[18]	✓	-	-	-	✓	✓	-	-	-
[19]	-	-	-	-	✓	-	-	-	-
[20]	-	-	-	-	✓	-	-	-	✓
[21]	-	-	-	-	✓	-	-	-	✓
[22]	-	✓	-	-	✓	-	-	-	✓
[23]	-	-	-	-	✓	-	-	-	-
[24]	-	-	-	-	✓	-	-	-	-
[25]	-	-	-	-	-	-	-	-	✓
[26]	-	✓	-	-	-	-	-	-	-
[27]	-	✓	-	-	✓	-	-	-	-
[28]	-	-	-	-	✓	-	-	-	-
[29]	-	✓	-	-	-	-	-	-	✓
[30]	✓	✓	-	-	✓	-	-	-	-
[31]	-	✓	-	-	✓	-	-	-	-
[32]	-	✓	-	-	✓	-	-	-	-
[33]	✓	-	-	-	✓	-	-	-	-
[34]	-	-	-	-	✓	-	-	-	-
[35]	✓	-	-	-	✓	-	-	-	-
[36]	-	✓	-	-	✓	✓	-	-	-
[37]	✓	-	-	-	-	-	-	-	✓
[38]	-	-	-	-	✓	-	-	-	-
[39]	✓	✓	-	-	-	-	-	-	✓
[40]	✓	-	-	-	✓	-	-	-	✓
Our work	✓	✓	✓	✓	✓	✓	✓	✓	✓

1.3. Contributions

This work proposes resilience enhancement of the smart urban electrical and gas grids considering pre-event responses against hurricanes at day-ahead. The poles outage-based-scenario modeling in the electrical distribution grid is regarded as a natural event. The pre-event responses are implemented by using reserve scheduling via BGs, DRP, and SSs for the prevention of the blackout during the event. The implementation of the reserve scheduling is done with attention to the maximum probability of blackout in areas through microgrid formation. The installing BGs, SSs and DRP implementation is scheduled subject to microgrids in areas with maximum blackout. The DRP is proposed based on various offer prices to industrial, commercial, and residential sections for demand management. Also, onsite strategy is considered for SSs in order to meeting residential demand with high population density. Minimizing the reserve costs, minimizing the consumers' dissatisfaction, and maximizing the resilience index of the electrical distribution grid are modeled as tri-objectives from operator's viewpoint. The optimization of the objectives by using augmented ε-constraint and max-min fuzzy methods in GAMS software is carried out. Accordingly, key contributions of our work can summarize as follow:

1) The reserve scheduling for resilience enhancement of the smart urban electrical and gas grids based on pre-event responses is proposed.
2) The pre-event responses are scheduled by BGs, DRP, and SSs for the prevention of the blackout.
3) The DRP is proposed for demand shaving and reducing blackout based on offer prices.
4) The onsite supply strategy is proposed by SSs in the residential demand.
5) The microgrid formation is proposed subject to damaged areas for installing BGs, SS and DRP implementing in the electrical distribution grid.
6) Tri-objectives such as minimizing the reserve costs, minimizing the consumers' dissatisfaction, and maximizing the resilience index are proposed.

1.4. Paper outline

The outline of paper is as follow: The poles outage is modeled in section 2. The modeling microgrid formation is proposed in section 3. The proposed reserve strategies are presented in section 4. In section 5, objective functions are modeled. The constraints are presented in section 6. In section 7, solution procedure is introduced. The numerical simulation and Case studies are proposed in section 8. Finally, in section 9, conclusions are drawn.

2. Modeling poles outage in the electrical distribution grid

As mentioned before, hurricanes are the most common natural event with high wind speed. This event leads to damaged poles in the electrical distribution grids, whereby wide blackout can make. In this section, scenario modeling-based fragility function of the poles is proposed for status of the electrical distribution grid against wind speed at day-ahead. In Fig.3. Failure probability of the poles considering different wind speed of the hurricane is depicted [41]. Regarding this figure, fragility function of the poles based on failure probability can be formulated by equation (1). In following, poles status by using fragility function can be modeled by Monte Carlo methodology via scenario modeling or random number generation. The poles status is formulated by equation (2) considering tolerance threshold of the poles subject to fragility function [42].

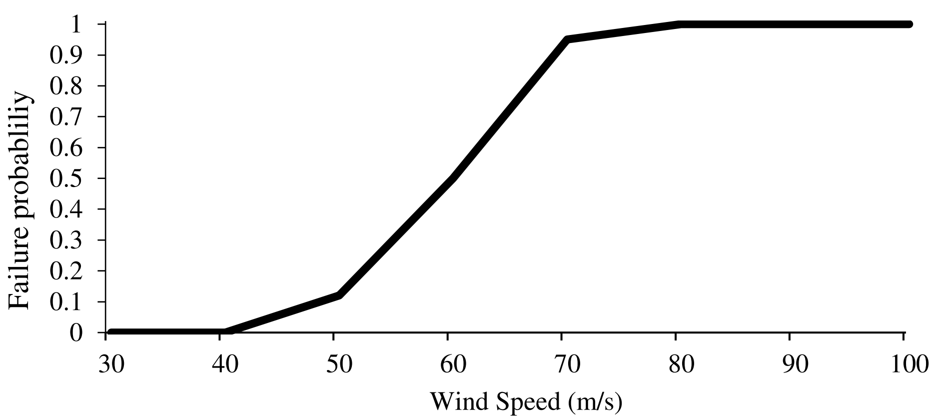


Fig.3. Failure probability of the poles with different wind speeds [41].

$$f_{poles}(v) = \begin{cases} 1 & v \geq v_{ine} \\ f_{poles}^{hw}(v) & v_{cr} < v < v_{ine} \\ 0 & v < v_{cr} \end{cases} \tag{1}$$

$$PS(p,v,s) = \begin{cases} 0 & f_{pole}(v) > pt(s) \\ 1 & f_{pole}(v) < pt(s) \end{cases} \tag{2}$$

In equation (2), *PS (p,v)* is the status of the *pth* pole in wind speed *v* and scenario *s*. Also, pole status considering fragility function and tolerance threshold of the poles is modeled by equation (2), in which 1=health status and 0=damaged status. The Monte Carlo methodology is proposed for the generation of the random variables or scenarios in the interval [0,1] for the tolerance threshold of the poles *{pt(s)}*. In this method, if *{pt(s)}* is more than the fragility function, the pole is healthy, and if low than the fragility function is damaged. Thus, probability of the poles in the scenarios generated can be obtained as follow:

$$\pi(s) = \prod_{s=1}^{S} pt(s) \tag{3}$$

3. Modeling microgrid formation

In this section, microgrid formation considering damage status of the poles in electrical distribution grid is modeled. The microgrid formation is done for installing BGs, SSs and implementing DRP in damaged areas subject to status of poles. The modeling microgrids formation is as follow:

$$MG(i,s) = \begin{cases} 1 & f_{pole}(p,v) > pt(p,s) \\ 0 & f_{pole}(p,v) < pt(p,s) \end{cases} \tag{4}$$

In equation (4), microgrid formation is done considering the damage status of the *pth* pole in scenario *s*. In this equation, 1= microgrid is formed in the damaged area, and 0=healthy area. The BGs are installed in the damaged poles in microgrids, and SSs are installed in the residential section in the microgrids. However, DRP is done for all consumers in the industrial, commercial, and residential sections in microgrids or damaged areas.

4. Modeling reserve strategies

In this section, reserve strategies are modeled as pre-event responses for resilience enhancement at day-ahead. These strategies are implemented with attention to identification of vulnerable areas or damaged poles by operators in the electrical distribution grid. The modeling reserve strategies are as follow:

4.1. Installing BG

The installing BGs are modeled considering number of the microgrids in the damaged poles. Actually, number of the BGs is equal to formed microgrids number in the electrical distribution grid. Hence, installing BGs can be modeled as follow:

$$N_{BG}(bg,s)=\begin{cases}1 & f_{pole}(p,v)>pt(p,s)\\ 0 & f_{pole}(p,v)<pt(p,s)\end{cases} \tag{5}$$

In equation (5), 1=BG is installed in damaged pole in scenario *s*.

4.2. Installing SS

As mentioned before, installation of the SSs in the microgrids for residential section with high consumption and population density is considered by onsite supply strategy. Hence, number of the SSs is equal to number of the residential buildings in the microgrids or damaged areas. The SSs installation is modeled as follow:

$$N_{SS}(ss,s)=MG(i,RC,s) \qquad \forall s,ss,rc \tag{6}$$

4.3. Implementing DRP

The implementation of the DRP is taken into account for industrial, commercial, and residential consumers in the microgrids subject to bid prices for demand reduction as a pre-event response against day-ahead blackout. The bid prices of the DRP implementation are different for industrial, commercial, and residential consumers. The DRP is modeled as follow:

$$C_{RC}=\sum_{s=1}^{S}\pi(s)\sum_{i=1}^{m}\sum_{rc=1}^{RC}\sum_{t=1}^{T}\zeta_{RC}\times D_{RC}^{DRP}(s,t) \qquad \forall s,i,rc,t \tag{7}$$

$$C_{CC}=\sum_{s=1}^{S}\pi(s)\sum_{i=1}^{m}\sum_{cc=1}^{CC}\sum_{t=1}^{T}\zeta_{CC}\times D_{CC}^{DRP}(s,t) \qquad \forall s,i,cc,t \tag{8}$$

$$C_{IC}=\sum_{s=1}^{S}\pi(s)\sum_{i=1}^{m}\sum_{ic=1}^{IC}\sum_{t=1}^{T}\zeta_{IC}\times D_{IC}^{DRP}(s,t) \qquad \forall s,i,ic,t \tag{9}$$

Where equations (7)-(9) are reserve costs of the DRP for residential, commercial and industrial consumers, respectively. In Fig.4. the DRP modeling for consumers is shown.

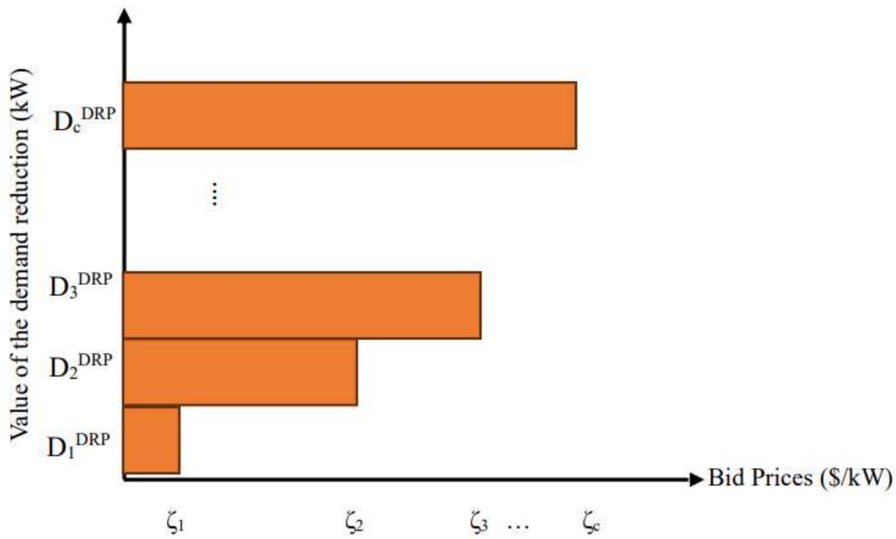


Fig.4. DRP modeling for consumers.

5. Modeling objective functions

In this section, objective functions of the resilience enhancement from view point of the operators are modeled as multi-objective functions such as 1) minimizing the reserve costs, 2) minimizing the consumers' dissatisfaction and 3) maximizing the resilience index. The objectives are modeled as follow:

5.1. Minimizing the reserve costs

The modeling reserve costs as first objective function in microgrids or damaged areas is formulated as follow:

$$\min f_1 = \sum_{s=1}^{S} \pi(s) \sum_{i=1}^{m} \sum_{t=1}^{T} \left\{ \sum_{bg=1}^{BG} C_{BG}(s,t,bg) + \sum_{ss=1}^{SS} C_{SS}(s,t,ss) + C_{RC}(s,t) + C_{CC}(s,t) + C_{IC}(s,t) \right\} \quad (10)$$

Where:

$$C_{BG}(s,t,bg) = \lambda_{gas}(t) \times P_{BG}(s,t,bg) \qquad \forall s,t,bg \quad (11)$$

$$C_{SS}(s,t,ss) = \lambda_{SS} \times \left\{ P_{SS}^{CH}(s,t,ss) + P_{SS}^{DCH}(s,t,ss) \right\} \qquad \forall s,t,ss \tag{12}$$

Where equations (11) and (12) are reserve costs of the BGs and SSs in the microgrids, respectively.

5.2. Minimizing the consumers' dissatisfaction

Minimizing the consumers' dissatisfaction is proposed as the second objective function by (13). The consumers' dissatisfaction is modeled considering the non-supplied demand for the consumers in the microgrids.

$$\min f_2 = \sum_{s=1}^{S} \pi(s) \sum_{i=1}^{m} \sum_{t=1}^{T} \left\{ \frac{D_{nsd}(s,i,t)}{D_{eq}(i,t)} \right\} \tag{13}$$

Where:

$$0 \le D_{nsd}(s,i,t) \le D_{eq}(i,t) \times \kappa(s,i,t) \qquad \forall s,i,t \tag{14}$$

$$\kappa(s,i,t) = \begin{cases} 1 & D_{eq}(i,t) > P_{BG}(s,t,bg) + P_{SS}^{DCH}(s,t,ss) \\ 0 & \qquad otherwise \end{cases} \tag{15}$$

The non-supplied demand limit is modeled by equation (14), and non-supplied demand state can be calculated by (15). In equation (15), 1= non-supplied demand is done, and 0=otherwise.

5.3. Maximizing the resilience index

Maximizing the resilience index is modeled based on ratio of the power generation than load demand in the microgrids. This objective function is proposed as third objective as follow:

$$\max f_3 = \sum_{s=1}^{S} \pi(s) \sum_{i=1}^{m} \sum_{t=1}^{T} \left\{ \frac{P_{BG}(s,i,t,bg) + P_{SS}^{DCH}(s,t,ss,rc)}{D_{eq}(i,t)} \right\} \tag{16}$$

6. Constraints modeling

The constraints of the optimization for resilience enhancement in the microgrids in the electrical distribution grid are modeled as follow:

6.1. Constraints of the SS

As mentioned before, installing SSs in microgrids is considered for residential consumers via onsite supply demand. The constraints are as follow:

$$0 \le P_{SS}^{DCH}(s,t,ss,rc) \le u_{ss}(s,t,ss,rc) \times P_{SS}^{r} \qquad \forall s,t,ss,i,rc \tag{17}$$

$$0 \le P_{SS}^{CH}(s,t,ss,rc) \le \left\{1 - u_{ss}(s,t,ss,rc)\right\} \times P_{SS}^{r} \qquad \forall s,t,ss,i,rc \tag{18}$$

$$\begin{aligned} &\mathrm{E}_{SS}(s,t,ss,rc) = \mathrm{E}_{SS}(s,t-1,ss,rc) \\ &+\left\{\left[\eta_{ss}^{CH} \times P_{SS}^{CH}(s,t,ss,rc)\right] - \left[\frac{1}{\eta_{ss}^{DCH}} \times P_{SS}^{DCH}(s,t,ss,rc)\right]\right\} \qquad \forall s,t,ss,i,rc \end{aligned} \tag{19}$$

$$\mathrm{E}_{SS}^{\min} \le \mathrm{E}_{SS}(s,t,ss,rc) \le \mathrm{E}_{SS}^{\max} \qquad \forall s,t,ss,i,rc \tag{20}$$

$$\left\{\left[\sum_{t=1}^{T} \frac{1}{\eta_{ss}^{DCH}} \times P_{SS}^{DCH}(s,t,ss,rc)\right] - \left[\sum_{t=1}^{T} \eta_{ss}^{CH} \times P_{SS}^{CH}(s,t,ss,rc)\right]\right\} = 0 \qquad \forall s,t,ss,i,rc \tag{21}$$

The power discharge and power charge of the SSs in the microgrids for each residential consumer are constrained by (17) and (18), respectively. The energy available of the SS and the limit of the energy available are modeled by (19) and (20), respectively. The constraint (21) represents the onsite supply strategy of SS for residential consumers.

6.2. Constraints of the BG

The BGs have constraints such as bound of the active and reactive powers generation as follow:

$$0 \le P_{BG}(s,i,t,bg) \le P_{BG}^{\max} \qquad \forall s,i,t,bg \tag{22}$$

$$0 \le Q_{BG}(s,i,t,bg) \le Q_{BG}^{\max} \qquad \forall s,i,t,bg \tag{23}$$

Where constraints (22) and (23) are bound of the active and reactive powers generation by BG, respectively.

6.3. Constraints of the energy flow balance

The energy flow constraints including the balance of the active and reactive powers and gas flow balance in the microgrids are modeled as follow:

$$\begin{aligned}
&\sum_{bg=1}^{BG} P_{BG}(s,i,t,bg)+\sum_{ss=1}^{SS} P_{SS}^{DCH}(s,t,ss,rc)+D_{nsd}(s,i,t)+D_{RC}^{DRP}(s,t,i,rc)+\\
&D_{CC}^{DRP}(s,t,i,cc)+D_{IC}^{DRP}(s,t,i,ic)-\sum_{ss=1}^{SS} P_{SS}^{CH}(s,t,ss,rc)-D_{eq}(s,i,t)\\
&=\sum_{a,b} V_a(s,i,t)\times V_b(s,t,b)\times Y_{a,b}\times\cos\left[\theta_{a,b}+\delta_b(s,t,b)-\delta_a(s,t,a)\right] \qquad \forall s,i,t,a,b
\end{aligned} \tag{24}$$

$$\begin{aligned}
&\sum_{bg=1}^{BG} Q_{BG}(s,i,t,bg)+Q_{nsd}(s,i,t)+Q_{RC}^{DRP}(s,t,i,rc)+Q_{CC}^{DRP}(s,t,i,cc)\\
&+Q_{IC}^{DRP}(s,t,i,ic)-Q_{eq}(s,i,t)\\
&=\sum_{a,b} V_a(s,i,t)\times V_b(s,t,b)\times Y_{a,b}\times\sin\left[\theta_{a,b}+\delta_b(s,t,b)-\delta_a(s,t,a)\right] \qquad \forall s,i,t,a,b
\end{aligned} \tag{25}$$

$$G_{GAS}(s,i,t)-\sum_{bg=1}^{BG} P_{BG}(s,i,t,bg)=G_{GAS}^{D}(s,i,t) \qquad \forall s,i,t \tag{26}$$

Where constraints (24)-(26) represent active power balance, reactive power balance and gas flow balance, respectively.

6.4. Constraints of the Voltage buses and power flow

The limit of the voltage buses and power flow in the lines are modeled by following constraints:

$$V_a^{\min} \le V_a(s,i,a) \le V_a^{\max} \qquad \forall s,i,a \tag{27}$$

$$\left|P_{a,b}(s,i,a,b)\right| \le P_{a,b}^{\max} \qquad \forall s,i,a,b \tag{28}$$

The constraints (27)-(28) are limit of the voltage buses and power flow in the lines, respectively.

7. Solution procedure

The augmented ε-constraint method is one of the solution procedures for solving multi-objective functions. This procedure has advantages such as simple implementation, acceptable convergence, and generation of efficient

Pareto frontier solutions and avoids inefficient ones. Accordingly, Pareto frontier solutions are obtained via augmented ε-constraint method by using following steps [43][44]:

1) Pay-off table or maximum and minimum ranges of the objective function must be calculated.
2) Considering one of the objectives as the main objective and putting on others objectives as a constraint.
3) Dividing objectives with constraint role by equal intervals to generation of the grid points or Pareto frontier solutions. The mathematical modeling of the augmented ε-constraint method is as follow:

$$\min\left[f_1(x)-\delta\sum_{n=1}^{N}\frac{s_n}{r_n}\right] \qquad 10^{-6}\le\delta\le10^{-3} \tag{29}$$

Subject to:

$$f_n(x)+s_n-\varepsilon_n^z \qquad n=2,3,...,N\,;s_n\in R^+ \tag{30}$$

$$\varepsilon_n^z=f_n^{\max}-\left[\frac{f_n^{\max}-f_n^{\min}}{q_n-1}\right]\times z \qquad z=0,1,...,q_n \tag{31}$$

Here x and δ are decision variables and scaling factor, respectively. And s_n and n are slack variable and *nth* objective function, respectively. The ε^z_n , r_n and q_n are *zth* range of *nth* objective, objectives range and equal intervals, respectively.

7.1. Max-min fuzzy method

In this subsection, max-min fuzzy method is proposed for choose the best trade-solution among Pareto frontier solutions in the tri-objective functions. The generated Pareto frontier solutions for tri-objective functions by augmented ε-constraint method have conflicting nature than others. Thus, max-min fuzzy method is introduced as decision making process by central operator for finding the best level of the objectives considering status of the electrical distribution grid. The following steps are done for finding the best solution [45]:

1) Using equations (32) and (33), all Pareto frontier solutions of the objective functions are formed as normalized states.
2) Regarding normalized values of the Pareto frontier solutions, minimum values of the objective functions should be determined by (34).

3) Finally, by (35) maximum rate of the obtained minimum value is determined as the best trade-off solution in among objective functions.

$$\vartheta_n^k = \begin{cases} 1 & f_n^k \le f_n^{\min} \\ \dfrac{f_n^{\max} - f_n^k}{f_n^{\max} - f_n^{\min}} & f_n^{\min} \le f_n^k \le f_n^{\max} \\ 0 & f_n^k \ge f_n^{\max} \end{cases} \quad \text{For minimizing objective functions} \tag{32}$$

$$\vartheta_n^k = \begin{cases} 1 & f_n^k \ge f_n^{\max} \\ \dfrac{f_n^k - f_n^{\min}}{f_n^{\max} - f_n^{\min}} & f_n^{\max} \ge f_n^k \ge f_n^{\min} \\ 0 & f_n^k \le f_n^{\min} \end{cases} \quad \text{For maximizing objective functions} \tag{33}$$

$$\vartheta_n^k = \min\left\{\vartheta_1^1, \dots, \vartheta_N^K\right\} \qquad \forall n = 1, \dots, N \qquad \forall k = 1, \dots, K \tag{34}$$

$$\vartheta^k = \max\left\{\min \vartheta_n^k\right\} \qquad \forall n = 1, \dots, N \qquad \forall k = 1, \dots, K \tag{35}$$

Where $\vartheta_n{}^k$ and $f^k{}_n$ are normalized solutions and value of the *nth* objective in *kth* solution, respectively.

8. Numerical simulation and Case studies

The proposed methodology for resilience enhancement is modeled by using numerical simulation. The pre-event responses are implemented by proposed reserve strategies considering the occurrence of the hurricane at day-ahead. Also, verifying the proposed methodology is analyzed by following case studies as follow:

Case I) Enhancement of the resilience by using BG installing.

Case II) Enhancement of the resilience by using BG and SS installing.

Case III) Enhancement of the resilience by installing BG, SS and implementing DRP.

In Fig.5. Process of the proposed methodology for resilience enhancement is shown. In this process, three steps are implemented as follow:

1) Modeling topological of the electrical distribution grid based on poles outage subject maximum wind speed at day-ahead and tolerance threshold of the poles. In this step, microgrids formation considering poles outage is implemented.
2) Modeling reserve strategies as pre-event responses based on installing BGs, SSs and implementing DRP in microgrids. In this step, objective functions subject to constraints are modeled.
3) Modeling solution procedures for solving objective functions based on proposed pre-event responses in the microgrids.

In this study, the hurricane has a maximum wind speed of 50 m/s on the day ahead, whereby the failure probability of the poles regarding Fig.3 is equal to 0.11. The proposed methodology is modeled on the 33-bus test distribution grid. It should be mentioned, it is assumed that the number of buses is equal to the number of poles. Using the Monte Carlo method, four scenarios are created for the tolerance threshold of the poles in the interval [0,1]. In Fig.6, generated scenarios for the tolerance threshold of the poles are depicted. The fourth scenario is selected to diminution of the computational burden in process of the proposed methodology. In the fourth scenario, poles 6, 12, and 26 are damaged by hurricane. The tolerance threshold of the mentioned poles is less than failure probability of the poles with wind speed of 50 m/s. It's assumed that wind speed 50 m/s is started at hour 10:00 at day-ahead. In Fig.7, the topology of the 33-bus test distribution grid with microgrids formation is shown. The residential, commercial, and industrial consumers in the microgrids are determined. As mentioned before, BGs are installed in damaged poles in the microgrids, and they are fed by urban gas. The gas price is equal to 14 $\$/m^3$. The data of the BGs are the same and are listed in Table 2. Regarding microgrid formation in Fig.7, there are three and two residential consumers in microgrids 1 and 2, respectively. Hence, five SSs are installed in the mentioned consumers. The information of the SS for meeting the electrical demand in the residential consumers using the onsite supply strategy is provided in Table 3. The cost of the SSs (λ_{SS}) in charging and discharging modes is equal to \$5. The electrical load demand of the microgrids is shown in Fig.8. Also, bid price for DRP implementation by residential, commercial and industrial consumers is presented in Fig.9. The DRP based on demand reduction considering bid price is presented. The numerical simulation is done by GAMS software in laptop system with CPU 3.33GHz and RAM 6GB.

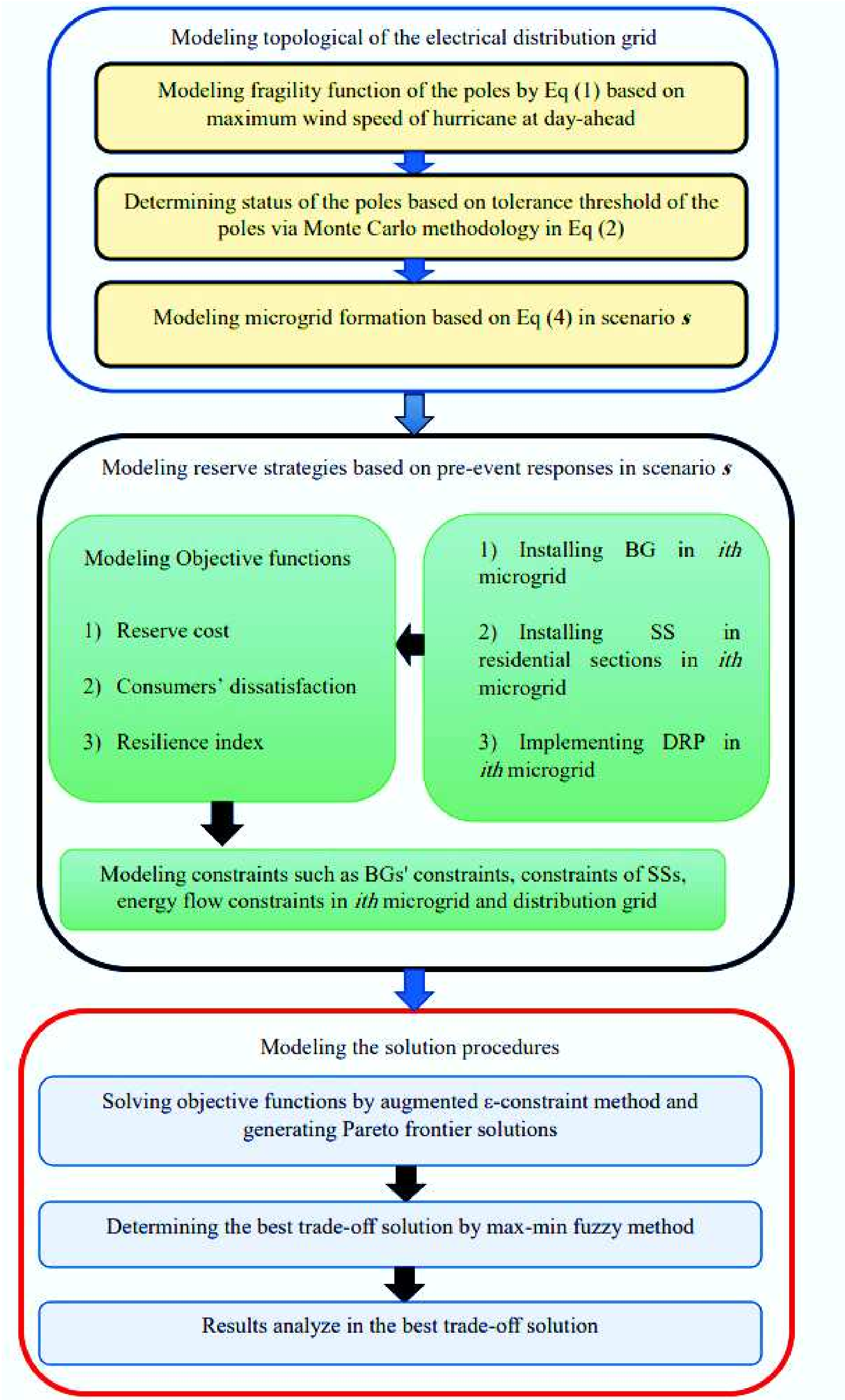

Modeling topological of the electrical distribution grid
Modeling fragility function of the poles by Eq (1) based on maximum wind speed of hurricane at day-ahead
Determining status of the poles based on tolerance threshold of the poles via Monte Carlo methodology in Eq (2)
Modeling microgrid formation based on Eq (4) in scenario *s*
Modeling reserve strategies based on pre-event responses in scenario *s*
Modeling Objective functions
1) Reserve cost
2) Consumers' dissatisfaction
3) Resilience index
1) Installing BG in *ith* microgrid
2) Installing SS in residential sections in *ith* microgrid
3) Implementing DRP in *ith* microgrid
Modeling constraints such as BGs' constraints, constraints of SSs, energy flow constraints in *ith* microgrid and distribution grid
Modeling the solution procedures
Solving objective functions by augmented ε-constraint method and generating Pareto frontier solutions
Determining the best trade-off solution by max-min fuzzy method
Results analyze in the best trade-off solution

Fig.5. Process of the proposed methodology for resilience enhancement.

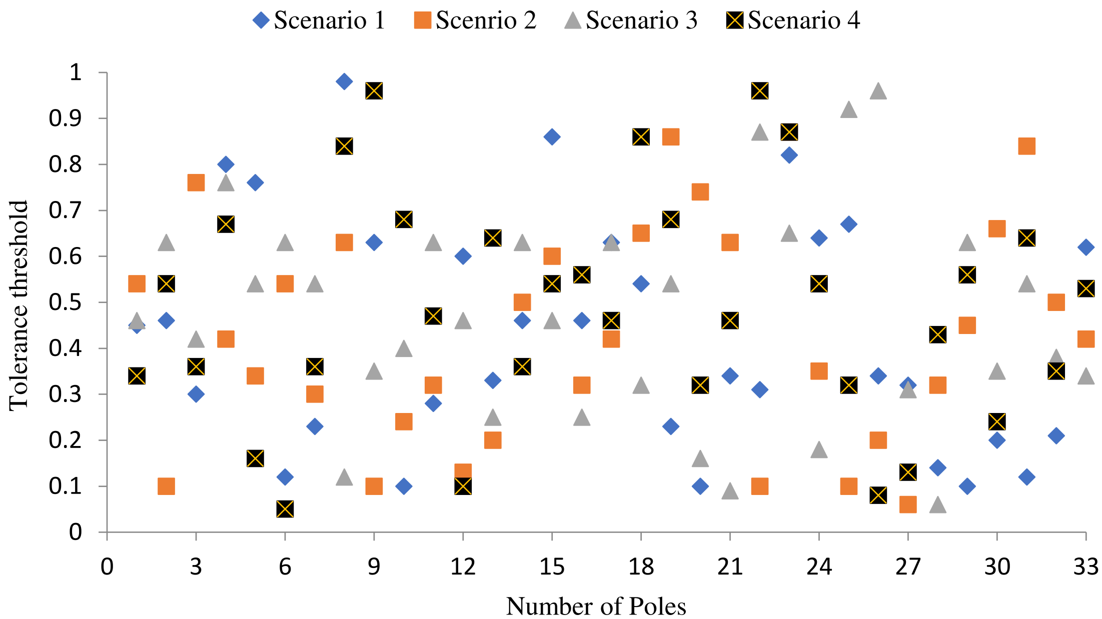


Fig.6. Tolerance threshold of the poles in all scenarios.

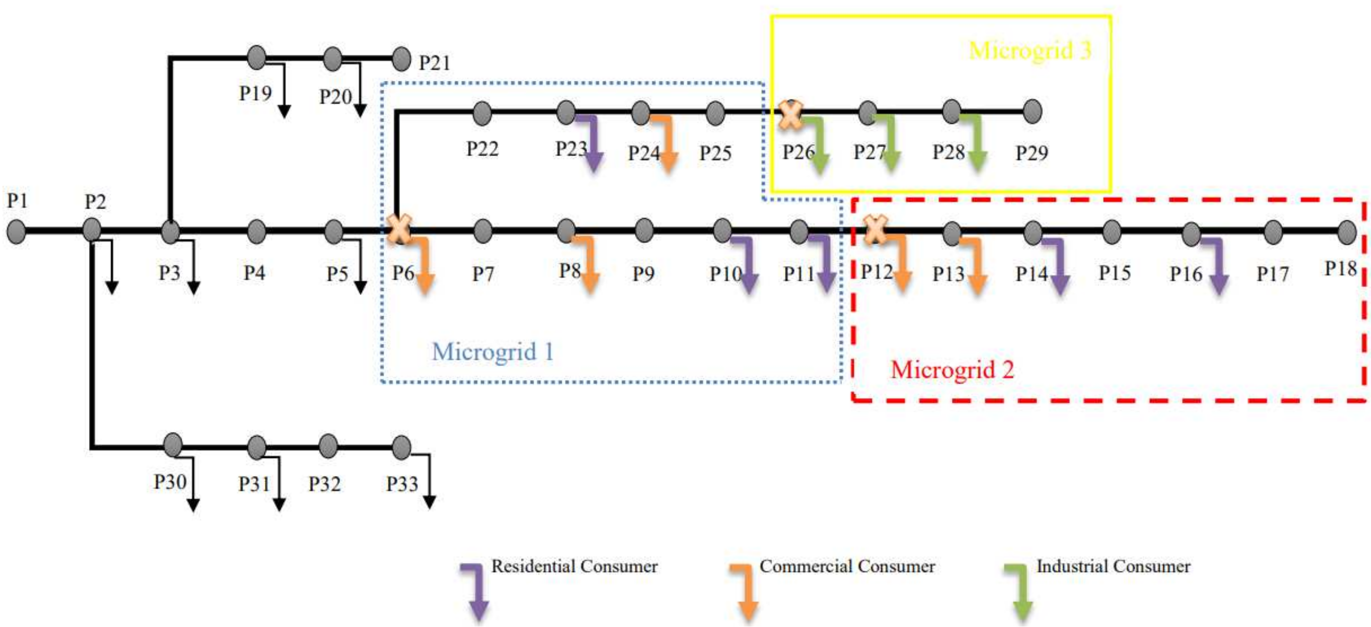


Fig.7. Microgrid formation considering damaged poles.

Table.2. BGs data in microgrids.

Parameters / BGs	P^{max} (kW)	Q^{max} (kVAr)	Location (Microgrid)	Installed in Pole
BG 1	800	650	1	6
BG 2	800	650	2	12
BG 3	800	650	3	26

Table.3. Data of SSs in the microgrids.

Parameters / SSs	P^{r} (kW)	E^{min} (%)	E^{max} (%)	η^{CH} (%)	η^{DCH} (%)	Location (Microgrid)	Installed in Pole
SS 1	20	10	100	95	90	1	10
SS 2	20	10	100	95	90	1	11
SS 3	20	10	100	95	90	1	23
SS 4	20	10	100	95	90	2	14
SS 5	20	10	100	95	90	2	16

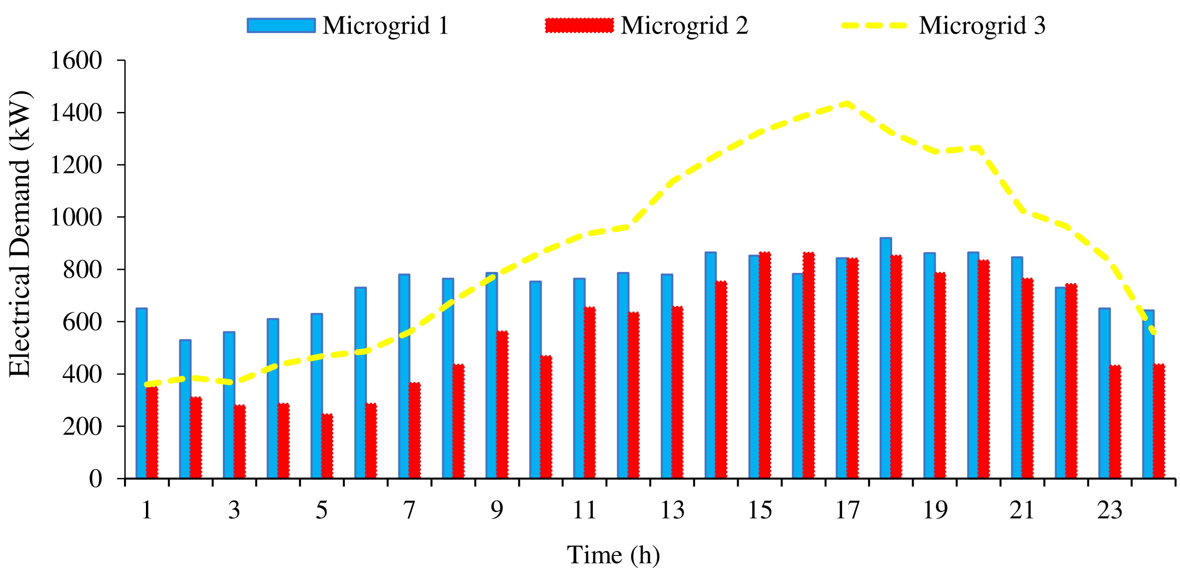
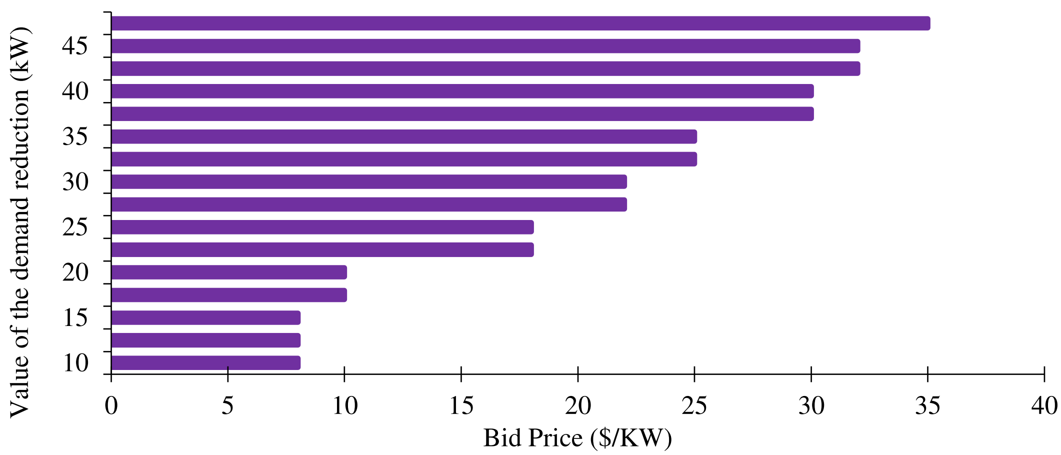
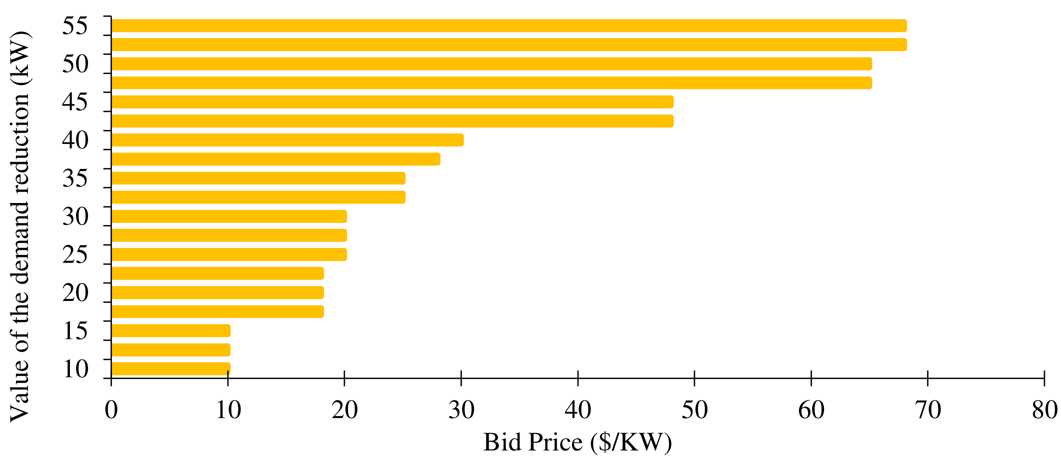


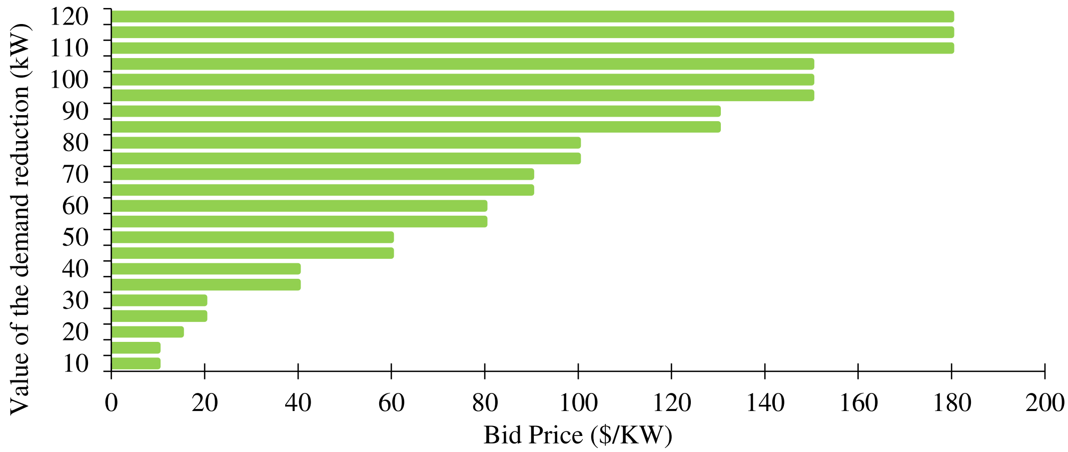
Fig.8. Electrical Load demand in the microgrids.


Value of the demand reduction (kW)
45
40
35
30
25
20
15
10
0
5
10
15
20
25
30
35
40
Bid Price ($/KW)

(a)


Value of the demand reduction (kW)
55
50
45
40
35
30
25
20
15
10
0
10
20
30
40
50
60
70
80
Bid Price ($/KW)

(b)



(c)

Fig.9. Bid price for DRP implementation. (a) Residential consumers, (b) Commercial consumers and (c) Industrial consumers.

8.1. Results and Discussion

In this subsection, results of the case studies implementation and impact of the reserve strategies on the objective functions are discussed. As mentioned before, the numerical simulation is carried out in the fourth scenario and implementation of the reserve strategies at hour 10:00 with maximum wind speed (50m/s) is done. The results of case studies are as follow:

Case I) In this case study, installation of the BGs is taken into account in damaged poles in the microgrids. The BGs are committed at hour 10:00 for meet demand in the microgrids. In Fig.10. Twelve solutions of the objective functions by using the augmented ε-constraint method are extracted. The best trade-off solution in red color is determined with maximum rate 0.63 by max-min fuzzy method. In the best trade-off solution, reserve cost as first objective, consumers' dissatisfaction as second objective and resilience index as third objective are equal to $268833.4, 13.3% and 86.6%, respectively. The reserve costs of the BGs 1,2 and 3 in the mirogrids are equal to $88790.9, $87686.2 and $92356.3, respectively. It visible, BG 3 in microgrid 3 has maximum reserve cost, due to high load demand of industrial consumers in microgrid 3.

In Table.4, Energy dispatch of the BGs and non-supplied demand in the mirogrids is listed. The non-supplied demand in the peak load hours of the microgrids is done, whereby BGs have not ability in meet demand. The total values of the non-supplied demand in the microgrids 1, 2 and 3 are equal to 454 kW, 256 kW and 4740 kW, respectively. In this case study, due to the low power limitation of the BGs in the supplying demand, high unmet demand is provided in microgrids, whereas consumers' dissatisfaction has the undesired level.

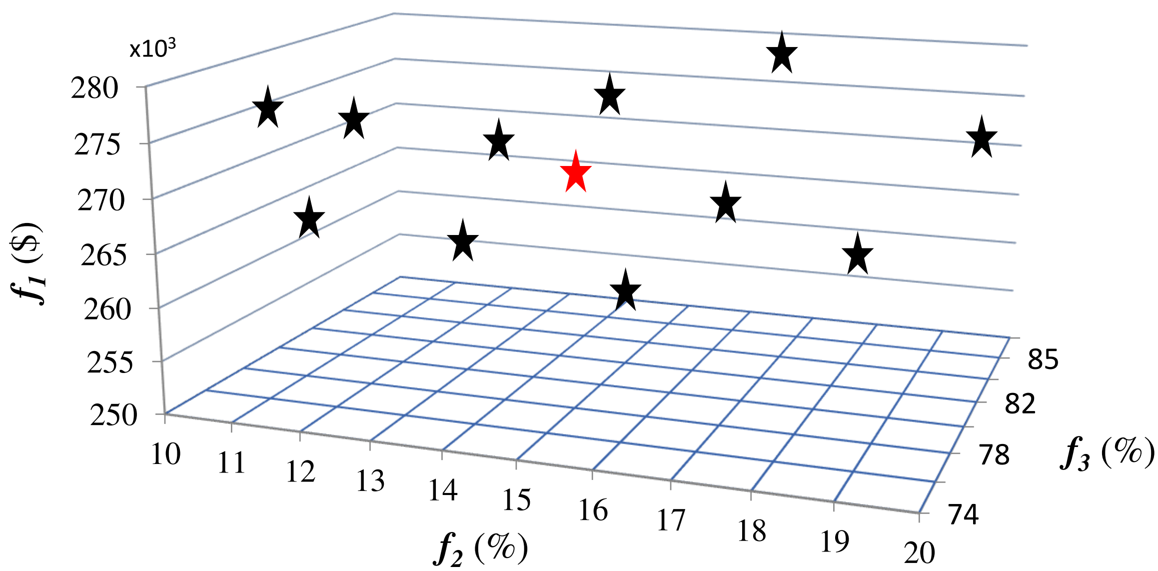


Fig.10. Pareto frontier solutions in Case I.

Table.4. Energy dispatch in the mirogrids in Case I.

Hour	BGs power generation (kW)			Non-supplied demand (kW)		
	BG 1	BG 2	BG 3	Microgrid 1	Microgrid 2	Microgrid 3
10	754	468	800	0	0	65
11	765	654	800	0	0	134
12	786	635	800	0	0	163
13	780	657	800	0	0	336
14	800	753	800	65	0	435
15	800	800	800	53	65	525
16	783	800	800	0	63	586
17	800	800	800	43	42	635
18	800	800	800	120	52	524
19	800	786	800	62	0	450
20	800	800	800	65	34	465
21	800	765	800	46	0	225
22	730	743	800	0	0	165
23	650	432	800	0	0	32
24	643	436	560	0	0	0

Case II) The participation of the SSs beside BGs is assumed in this case study. The operation of the SSs for the residential consumers in the microgrids 1 and 2 is considered via onsite supply strategy. The discharge powers of the SSs only are consumed by residential consumers. The generated Pareto frontier solutions for reserve costs, consumers' dissatisfaction and resilience index is shown in Fig.11. The amounts of the reserve cost, consumers' dissatisfaction and resilience index in the best trade-off solution are \$269546.7, 11.9% and 88.1%, respectively. It's visible, consumers' dissatisfaction in this case with participation of the SSs in the residential consumers is minimized by 1.4% than Case I, respectively. Also, resilience index in this case is enhanced by 1.5% in comparison to Case I. The participation of the SSs in this case has provided more generation capacity in the electrical grids for supply demand of the residential consumers.

The electrical energy dispatch of Case II is presented in Table 5. In microgrid 1, the charging power of SS 1, SS 2, and SS 3 are scheduled at hours 10:00, 12:00, and 11:00, respectively. Also, in microgrid 2, power injected to SS 4 at hours 10:00 and 19:00 is done, and SS 5 is charged at hour 12:00. However, the total power generation or discharging power of the SSs in microgrids 1 and 2 is equal to 56 kW and 47 kW, respectively. In this case study, non-supplied demand in the microgrids 1 and 2 with participation of the SSs is reduced up by 9.7% and 21.1%, than Case I, respectively. The discharged power of the SSs is scheduled in the peak hours for meeting electrical demand in the residential consumers.

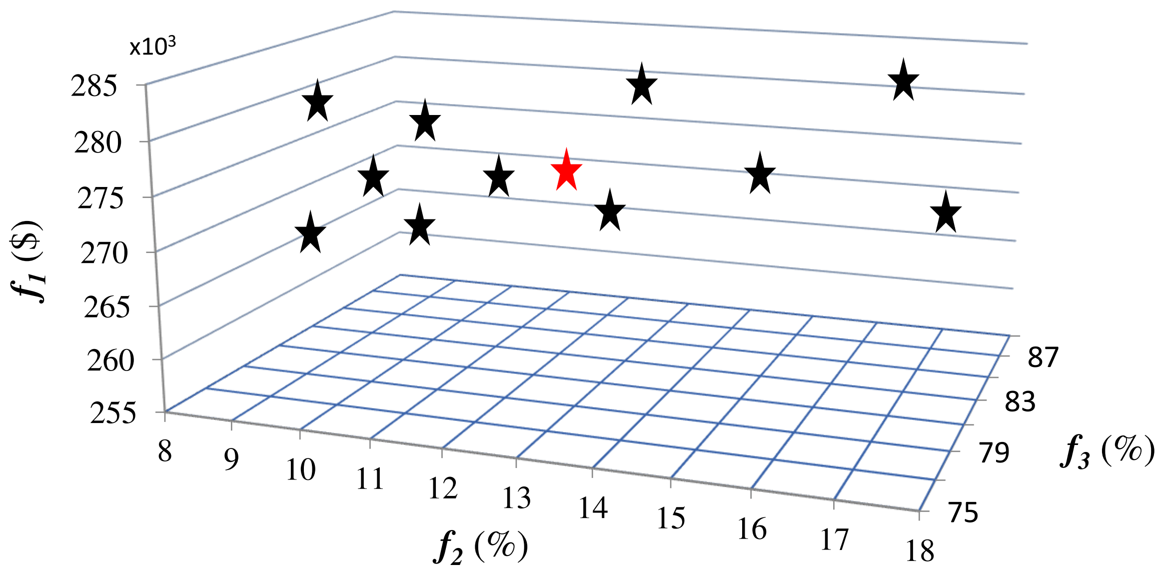


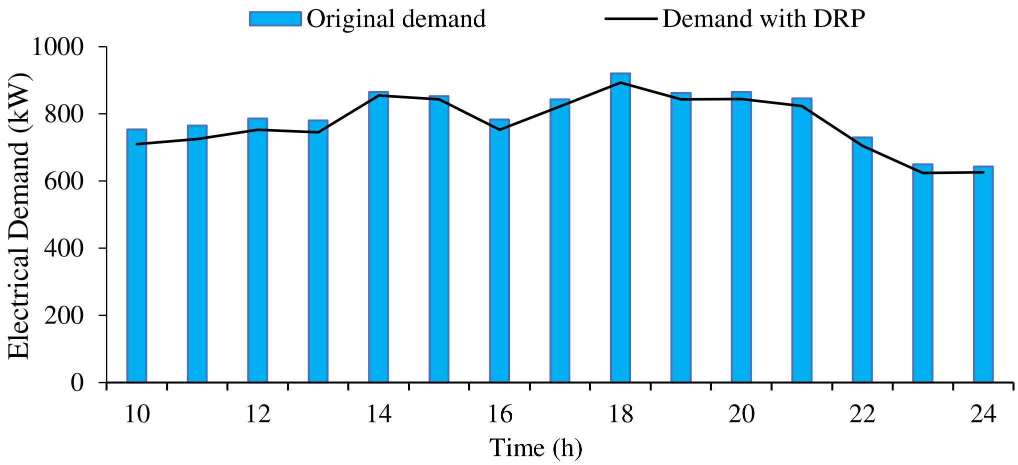
Fig.11. Pareto frontier solutions in Case II.

Table.5. Energy dispatch in the mirogrids in Case II.

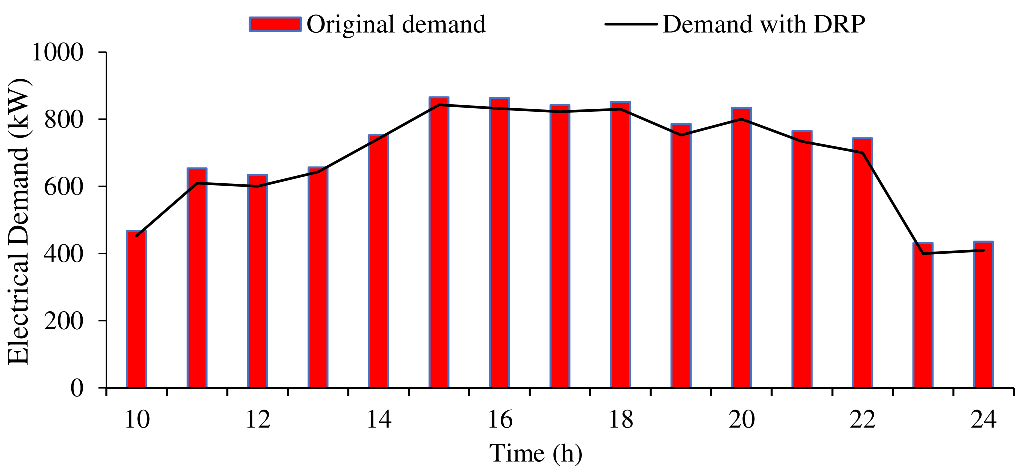
Hour	BGs power generation (kW)			SSs power dispatch (kW)					Non-supplied demand (kW)		
	BG 1	**BG 2**	**BG 3**	**SS 1**	**SS 2**	**SS 3**	**SS 4**	**SS 5**	**Microgrid 1**	**Microgrid 2**	**Microgrid 3**
10	775	491	800	-20	0	0	-20	0	0	0	65
11	765	664	800	0	0	-20	0	0	0	0	134
12	786	655	800	0	-10	0	0	-20	0	0	163
13	780	657	800	0	0	0	0	0	0	0	336
14	800	753	800	10	0	0	0	0	53	0	435
15	800	800	800	0	9	0	19	0	41	46	525
16	785.6	800	800	9.4	-10	0	0	0	0	63	586
17	800	800	800	0	0	0	0	0	43	42	635
18	800	800	800	0	9	11	0	19	100	33	524
19	800	796	800	0	0	0	-10	0	62	0	450
20	800	800	800	0	0	0	9	0	65	25	465
21	800	765	800	0	0	0	0	0	46	0	225
22	730	743	800	0	0	0	0	0	0	0	165
23	641.5	432	800	0	0	8.5	0	0	0	0	32
24	643	436	560	0	0	0	0	0	0	0	0

Case III) The operation of the DRP, SSs and BGs are implemented in this case study. In this case, DRP is performed for all consumers in microgrids with bidding pricing from operators in electrical demand reduction. In Fig.12. Implementation of the DRP on the electrical demand for all microgrids is shown. It should be mentioned, DRP is started at hour 10:00. The total electrical demand reduced by using DRP in microgrid 1, microgrid 2 and microgrid 3 are equal to 381.5 kW, 404.3kW and 630.4kW, respectively. Also, reduced electrical demand in all microgrids is almost done at all hours. The reduction of the electrical demand can lead to decrease power generation of the BGs and reserve costs. In Fig.13 values of the objective functions for reserve costs, consumers' dissatisfaction and resilience index in the best trade-off solution are equal to $263863.3, 9.6% and 90.4%, respectively. In this case, reserve cost is minimized by 1.8% and 2.1% than Cases I and II, respectively. As well, consumers' dissatisfaction is reduced up by 3.7% and 2.3% in comparison to Cases I and II, respectively. However, resilience index is improved by 3.8% and 3.2% than Cases I and II, respectively. The reserve costs of the BGs, SSs and DRP in all microgrids are equal to $250546.3, $1032.4 and $12284.6, respectively.

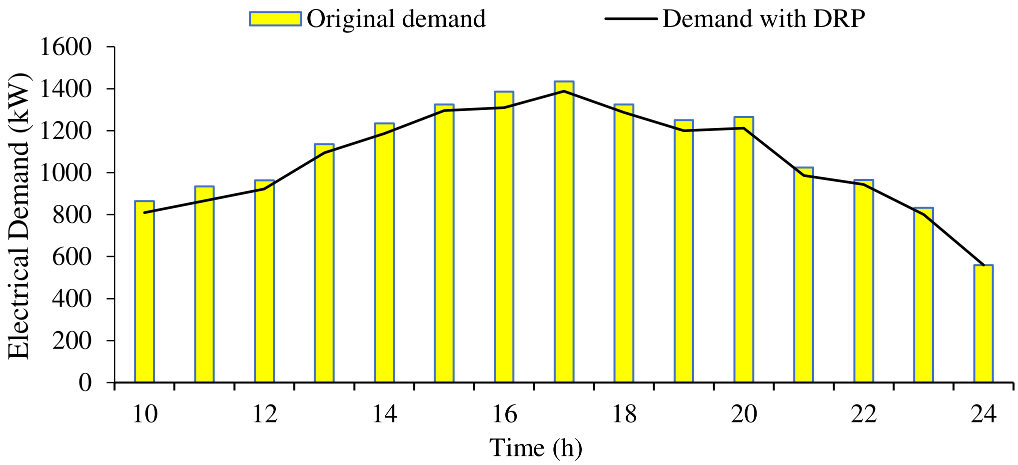
In Table.6, power dispatch of the BGs, SSs and non-supplied demand in Case III with DRP is provided. The total values of the non-supplied demand in microgrids 1, 2 and 3 are equal to 264.4kW, 87kW, 4101 kW, respectively. The minimization rate of the non-supplied demand in microgrids 1, 2 and 3 is equal to 41.76%, 66% and 13.48% in comparison with Case I, respectively. Also, discharged power of the SSs in peak demand of the residential consumers is occurred for reduce non-supplied demand. The DRP and operation of the SSs reduce the non-supplied demand, which optimally affects the reserve cost, consumers' satisfaction, and resilience index in microgrids.


Original demand
Demand with DRP
1000
800
600
400
200
0
Electrical Demand (kW)
10
12
14
16
18
20
22
24
Time (h)

(a)


Original demand
Demand with DRP
1000
800
600
400
200
0
Electrical Demand (kW)
10
12
14
16
18
20
22
24
Time (h)

(b)



(c)

Fig.12. Implementation of the DRP for all microgrids. (a) Microgrid 1, (b) Microgrid 2 and (c) Microgrid 3.

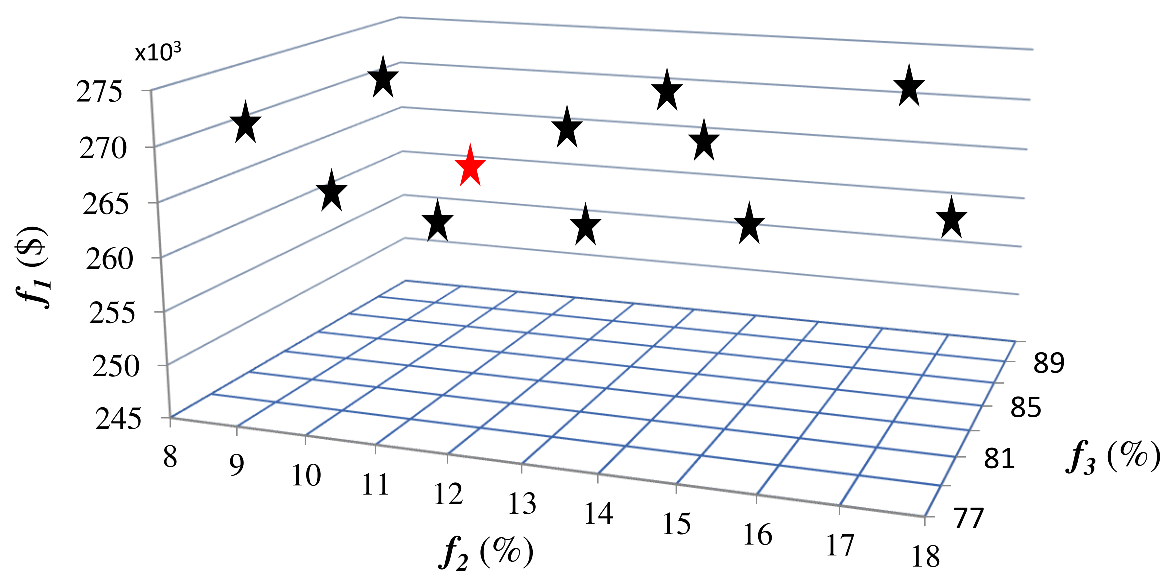


Fig.13. Pareto frontier solutions in Case III.

Table.6. Energy dispatch in the mirogrids in Case III.

Hour	BGs power generation (kW)			SSs power dispatch (kW)					Non-supplied demand (kW)		
	BG 1	**BG 2**	**BG 3**	**SS 1**	**SS 2**	**SS 3**	**SS 4**	**SS 5**	**Microgrid 1**	**Microgrid 2**	**Microgrid 3**
10	750	493	800	-20	-20	0	-20	-20	0	0	10
11	755	610	800	0	0	-20	0	0	0	0	66
12	753	600	800	0	0	0	0	0	0	0	123
13	745	643	800	0	0	0	0	0	0	0	295
14	800	742	800	0	0	19.6	0	0	35.4	0	386
15	800	800	800	0	0	0	0	20	43	23	496
16	753	800	800	0	0	0	0	0	0	32	510
17	800	800	800	0	0	0	0	0	22	22	588
18	800	800	800	19.6	20	0	20	0	54	10	486
19	800	753	800	0	0	0	0	0	43	0	400
20	800	800	800	0	0	0	0	0	44	0	412
21	800	734	800	0	0	0	0	0	23	0	186
22	705	700	800	0	0	0	0	0	0	0	143
23	624	400	800	0	0	0	0	0	0	0	0
24	626	410	560	0	0	0	0	0	0	0	0

9. Conclusion

This research study aimed to enhance the resilience of electrical distribution grids in urban areas by utilizing smart grid technologies. The study introduced the concept of pole outage caused by hurricane as a natural event, which is then used to generate scenarios through the pole fragility function. To improve resilience against such event, the study proposed day-ahead reserve scheduling as a pre-event response. The reserve scheduling strategy included three key components: the installation of BGs, the implementation of DRP, and the utilization of SSs with a focus on microgrid formation in the damaged areas. The BGs are supplied by urban gas grids to meet the electrical demand in the affected regions. The DRP is designed to manage the demand by offering price incentives to consumers for reducing their electricity consumption. Additionally, the SSs are operated by consumers as onsite supply strategy to meet their own electricity needs during the event. The proposed approach was implemented using a tri-objective framework, which aimed to minimize reserve costs, minimize consumers' dissatisfaction, and maximize the resilience index of the electrical distribution grid. The GAMS software and augmented ε-constraint method is utilized to solve the reserve scheduling problem. The examination of the proposed methodology is conducted through the analysis of three case studies as follow:

Case I) In this case, BGs are used in the microgrds. The reserve cost, consumers' dissatisfaction and resilience index have values \$268833.4, 13.3% and 86.6%, respectively.

Case II) The operation of the SSs and BGs are used in this case. The reserve cost, consumers' dissatisfaction and resilience index have values $269546.7, 11.9% and 88.1%, respectively.

Case III) Implementation of the DRP, SSs operation and BGs are considered in this case. The reserve cost, consumers' dissatisfaction and resilience index have values $263863.3, 9.6% and 90.4%, respectively.

The obtained results show that the proposed methodology for the resilience of the electrical distribution system can be enhanced during the hurricane as a natural event.

References

[1] G. Raman, J. C. -H. Peng and T. Rahwan, "Manipulating Residents' Behavior to Attack the Urban Power Distribution System," in IEEE Transactions on Industrial Informatics, vol. 15, no. 10, pp. 5575-5587, Oct. 2019, doi: 10.1109/TII.2019.2903882.

[2] J. Lopez, J. E. Rubio and C. Alcaraz, "A resilient architecture for the smart grid", *IEEE Trans. Ind. Inform.*, vol. 14, no. 8, pp. 3745-3753, Aug. 2018.

[3] M. Khederzadeh and S. Zandi, "Enhancement of Distribution System Restoration Capability in Single/Multiple Faults by Using Microgrids as a Resiliency Resource," in IEEE Systems Journal, vol. 13, no. 2, pp. 1796-1803, June 2019, doi: 10.1109/JSYST.2019.2890898.

[4] S. Ma, B. Chen and Z. Wang, "Resilience enhancement strategy for distribution systems under extreme weather events", *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1442-1451, Mar. 2018.

[5] Z. Wang and J. Wang, "Self-healing resilient distribution systems based on sectionalization into microgrids", *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 3139-3149, Nov. 2015.

[6] C. Y. Wang Hou, F. Qiu, S. Lei and K. Liu, "Resilience enhancement with sequentially proactive operation strategies", *IEEE Trans. Power Syst.*, vol. 32, no. 4, pp. 2847-2857, Jul. 2017.

[7] S. Poudel and S. Dubey, "Critical load restoration using distributed energy resources for resilient power distribution system", *IEEE Trans. Power Syst.*, vol. 34, no. 1, pp. 52-63, Jan. 2019.

[8] K. S. A. Sedzro, A. J. Lamadrid and L. F. Zuluaga, "Allocation of resources using a microgrid formation approach for resilient electric grids", *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2633-2643, May 2018.

[9] Mathaios Panteli and Pierluigi Mancarella. Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. Electric Power Systems Research. 127. 259–270. 2015.

[10] R. J. Campbell. Weather-related power outages and electric system resiliency. Congressional Res. Service, Washington, DC, USA, Tech. Rep. 7-5700, 2012.

[11] Christoph Mazur et al. A holistic resilience framework development for rural power systems in emerging economies. Applied Energy. 235. 219–232. 2019.

[12] Mahzarnia M and et al. A Review of the Measures to Enhance Power Systems Resilience. IEEE Systems Journal. 3. 4059 – 4070. 2020.

[13] Javad Najafi et al. Power Distribution System Improvement Planning under Hurricanes Based on a New Resilience Index. Sustainable Cities and Society. 39.592-604.2018.

[14] W. Zhang, T. Qian, X. Chen, K. Huang, W. Tang and Q. Wu, "Resilient Economic Control for Distributed Microgrids Under False Data Injection Attacks," in IEEE Transactions on Smart Grid, vol. 12, no. 5, pp. 4435-4446, Sept. 2021, doi: 10.1109/TSG.2021.3073874.

[15] Y. Xu, C.-C. Liu, K. Schneider, F. Tuffner and D. Ton, "Microgrids for service restoration to critical load in a resilient distribution system", *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 426-437, 2018.

[16] R. Marsh, Congressman: National Power Grid Frequently Attacked, 2015, [online] Available: https://edition.cnn.com/2015/10/21/politics/national-power-grid-cyber-attacks/index.html.

[17] Q. Zhou, M. Shahidehpour, A. Alabdulwahab and A. Abusorrah, "A cyber-attack resilient distributed control strategy in islanded microgrids", *IEEE Trans. Smart Grid*, vol. 11, no. 5, pp. 3690-3701, Sep. 2020.

[18] Chen, Y., Wang, J., Bo, R., Gu, C., & Li, Q. (2023). Risk-Averse scheduling of integrated electricity-heat systems considering multi-energy network operations for resilience enhancement against contingencies. *International Journal of Electrical Power & Energy Systems*, *153*, 109313.

[19] Ghosh, P., & De, M. (2023). A stochastic investment decision making method for distribution system resilience enhancement considering automation, hardening and distributed energy resources. *Reliability Engineering & System Safety*, *237*, 109395.

[20] Ebbrecht, G., & Chen, J. (2023). Enhancing equitable resilience of urban energy systems via strategic planning of EV charging infrastructure. *The Electricity Journal*, *36*(5), 107275.

[21] Dong, Z., Zhang, X., Zhang, N., Kang, C., & Strbac, G. (2023). A distributed robust control strategy for electric vehicles to enhance resilience in urban energy systems. *Advances in Applied Energy*, *9*, 100115.

[22] Wang, Z., Ding, T., Mu, C., Huang, Y., Yang, M., Yang, Y., ... & Li, M. (2023). A distributionally robust resilience enhancement model for transmission and distribution coordinated system using mobile energy storage and unmanned aerial vehicle. *International Journal of Electrical Power & Energy Systems*, *152*, 109256.

[23] Gautam, M., & Benidris, M. (2023). A graph theory and coalitional game theory-based pre-positioning of movable energy resources for enhanced distribution system resilience. *Sustainable Energy, Grids and Networks*, 101095.

[24] Ahmadi, S. E., Marzband, M., Ikpehai, A., & Abusorrah, A. (2022). Optimal stochastic scheduling of plug-in electric vehicles as mobile energy storage systems for resilience enhancement of multi-agent multi-energy networked microgrids. *Journal of Energy Storage*, *55*, 105566.

[25] Shahbazi, A., Aghaei, J., Niknam, T., Ardeshiri, M., Kavousi-Fard, A., & Shafie-khah, M. (2022). Potential of Mobile Energy Hubs for Enhancing Resilience of Electricity Distribution Systems. *Electric Power Systems Research*, *213*, 108749.

[26] Mishra, D. K., Ghadi, M. J., Li, L., Zhang, J., & Hossain, M. J. (2022). Active distribution system resilience quantification and enhancement through multi-microgrid and mobile energy storage. *Applied Energy*, *311*, 118665.

[27] Hashemifar, S. M. A., Joorabian, M., & Javadi, M. S. (2022). Two-layer robust optimization framework for resilience enhancement of microgrids considering hydrogen and electrical energy storage systems. *International Journal of Hydrogen Energy*, *47*(79), 33597-33618.

[28] Sun, Q., Wu, Z., Ma, Z., Gu, W., Zhang, X. P., Lu, Y., & Liu, P. (2022). Resilience enhancement strategy for multi-energy systems considering multi-stage recovery process and multi-energy coordination. *Energy*, *241*, 122834.

[29] Javadi, E. A., Joorabian, M., & Barati, H. (2022). A sustainable framework for resilience enhancement of integrated energy systems in the presence of energy storage systems and fast-acting flexible loads. *Journal of Energy Storage*, *49*, 104099.

[30] Ahmadi, S., Khorasani, A. H. F., Vakili, A., Saboohi, Y., & Tsatsaronis, G. (2022). Developing an innovating optimization framework for enhancing the long-term energy system resilience against climate change disruptive events. *Energy Strategy Reviews*, *40*, 100820.

[31] Rajabzadeh, M., & Kalantar, M. (2022). Enhance the resilience of distribution system against direct and indirect effects of extreme winds using battery energy storage systems. *Sustainable Cities and Society*, *76*, 103486.

[32] Ni, F., Zheng, Z., Xie, Q., Xiao, X., Zong, Y., & Huang, C. (2021). Enhancing resilience of DC microgrids with model predictive control based hybrid energy storage system. *International Journal of Electrical Power & Energy Systems*, *128*, 106738.

[33] Aldarajee, A. H., Hosseinian, S. H., & Vahidi, B. (2020). A secure tri-level planner-disaster-risk-averse replanner model for enhancing the resilience of energy systems. *Energy*, *204*, 117916.

[34] Dwivedi, D., Yemula, P. K., & Pal, M. (2023). Evaluating the Planning and Operational Resilience of Electrical Distribution Systems with Distributed Energy Resources using Complex Network Theory. *Renewable Energy Focus*.

[35] Wang, Y., Yang, Y., & Xu, Q. (2023). Integrated planning of natural gas and electricity distribution systems for enhancing resilience. *International Journal of Electrical Power & Energy Systems*, *151*, 109103.

[36] Sui, Q., Li, F., Wu, C., Feng, Z., Lin, X., Wei, F., & Li, Z. (2022). Optimal scheduling of battery charging–swapping systems for distribution network resilience enhancement. *Energy Reports*, *8*, 6161-6170.

[37] Zhou, J., Coit, D. W., Felder, F. A., & Tsianikas, S. (2023). Combined optimization of system reliability improvement and resilience with mixed cascading failures in dependent network systems. *Reliability Engineering & System Safety*, *237*, 109376.

[38] Saini, D. K., & Sharma, M. (2021). Techno-economic hardening strategies to enhance distribution system resilience against earthquake. *Reliability Engineering & System Safety*, *213*, 107682.

[39] Wang, H., Hou, K., Zhao, J., Yu, X., Jia, H., & Mu, Y. (2022). Planning-Oriented resilience assessment and enhancement of integrated electricity-gas system considering multi-type natural disasters. *Applied Energy*, *315*, 118824.

[40] Rahiminejad, A., Ghafouri, M., Atallah, R., Lucia, W., Debbabi, M., & Mohammadi, A. (2023). Resilience enhancement of Islanded Microgrid by diversification, reconfiguration, and DER placement/sizing. *International Journal of Electrical Power & Energy Systems*, *147*, 108817.

[41] Abdullahi M. Salman & Yue Li (2016) Age-dependent fragility and life-cycle cost analysis of wood and steel power distribution poles subjected to hurricanes, Structure and Infrastructure Engineering, 12:8, 890-903, DOI: 10.1080/15732479.2015.1053949

[42] Li, Y., Xie, K., Wang, L., & Xiang, Y. (2019). Exploiting network topology optimization and demand side management to improve bulk power system resilience under windstorms. *Electric Power Systems Research*, *171*, 127-140.

[43] Mavrotas, G. (2009). Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. *Applied mathematics and computation*, *213*(2), 455-465.

[44] Amjady, N., Aghaei, J., & Shayanfar, H. A. (2009). Stochastic multiobjective market clearing of joint energy and reserves auctions ensuring power system security. *IEEE Transactions on Power Systems*, *24*(4), 1841-1854.

[45] Chamandoust, H., Derakhshan, G., Hakimi, S. M., & Bahramara, S. (2019). Tri-objective optimal scheduling of smart energy hub system with schedulable loads. *Journal of Cleaner Production*, *236*, 117584.