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An Efficient Interactive Framework for Improving Resilience of Power-Water Distribution Systems with Multiple Privately-owned Microgrids

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Abstract: Resilience improvement of power distribution networks against natural disasters is an important problem. Water network similar to other important infrastructures depends on power networks. In this paper, resilience improvement is defined as increasing the users' accessibility to water and power after natural disasters. Microgrids with appropriate operation can provide energy to restore disconnected loads in distribution networks. In the proposed interactive framework, a stochastic energy management program for microgrids is designed that not only determines the amount of energy can be delivered to distribution systems, but also considers the reliability of local loads during emergency conditions. Each microgrid provides a list of bid-quantity energy blocks to the distribution system operator (DSO) during the emergency period. Then, the DSO chooses the best plan to restore disconnected loads considering inaccessibility values to power and water and also the damage of power and water distribution networks. Demand response actions in microgrids are also considered as effective tools for the energy management program, and their impact on the distribution system resilience is investigated. The proposed model is tested on the modified IEEE 33-bus distribution system with multiple microgrids, and the effectiveness of the proposed method is validated accordingly.

Keywords: Microgrids, natural disasters, resilience, stochastic linear programming, water network.

NOMENCLATURE

Indices and Sets

c, C_m	Index and number of curtailable loads in microgrid m
d, D	Index and number of incentive steps
g, G_m	Index and number of generators in microgrid m
i, j	Bus indexes in distribution system
l, N	Index and number of loads in distribution system
m, mg	Index and number of microgrids
mg_w	Number of microgrids which are implemented for restoration in (islanded or main) network w
$N_b^w, N_{line}^w, N_l^w, N_{mg}^w$	Number of buses, lines, loads and microgrids in (islanded or main) network w

s, S	Index and number of scenarios
t, t'	Time indices
w, W	Index and number of networks (islanded or main)
<i>Parameters and Constants</i>	
$A(g, m), B(g, m)$	Cost-function coefficients of dispatchable generator g in microgrid m
B_{ij}	Line susceptance between bus i and j
$FAT(s, m)$	Fuel arrival time to microgrid m in scenario s
$Fuel_{cap}^{avial}(m)$	Available fuel capacity in microgrid m
$CVLIP_{l,t}$	Cost value of inaccessibility of load l to power at time t
$CVLIW_{l,t}$	Cost value of inaccessibility of load l to water at time t
G_{ij}	Line conductance between bus i and j
$\left I_{ij}^{\max} \right $	Maximum allowable current of line between bus i and j
$inprc(d)$	Incentive price at step d
LI_i	Importance coefficient of load i
$lf(t)$	Distribution system load variation coefficients
$load(t, s, m)$	Active power demand of microgrid m at time t in scenario s
$load_{shift}^{\max}(m)$	Maximum amount of shiftable load of microgrid m
$load_{cur}^{\max}(c, m)$	Maximum active power of curtailable load c in microgrid m
$P_{l,t}^w$	Active power of load l at time t in (islanded or main) network w
$P^{\min}(g, m), P^{\max}(g, m)$	Minimum/maximum active power of generator g
$P_{i,t}^w$	Active power injected into bus i at time t in (islanded or main) network w
$pchr_{\max}, pdch_{\max}$	Maximum rate of charging/discharging power of battery
$pr(s)$	Probability of each scenario
$Q_i^{resource}$	Capacity of reactive compensation which is installed at bus i
$Q_{l,t}^w$	Reactive power of load l at time t in (islanded or main) network w
$Q_{i,t}^w$	Reactive power injected into bus i at time t in (islanded or main) network w
$R^{DN}(g, m), R^{UP}(g, m)$	Ramp down/up rate of generator g in microgrid m
$Scap^{\max}(m)$	Maximum point of common coupling (PCC) power exchange of microgrid m to distribution network
$SOC_{\min}(m), SOC_{\max}(m)$	Minimum/maximum active power of battery in microgrid m
$SUC(g, m), SDC(g, m)$	Start-up/shut-down cost of generator g in microgrid m
$Tload_{cur}^{\max}(c, m)$	Maximum duration of curtailable load c in microgrid m
t_0	The initial time of the emergency period
T_c	Emergency time duration
t_h	The time within the emergency period that the load of distribution system is minimum
$ V_{\min} , V_{\max} $	Minimum/maximum allowable voltage of buses
$VOLL(m)$	Value of lost load in microgrid m
$\eta(m)$	Efficiency of battery charging or discharging in microgrid m
$\rho(t)$	Market price at time t
<i>Functions and variables</i>	
$inprc^{win}(m)$	Incentive price which is accepted by DSO to purchase energy from microgrid m
LSF_l	Satisfaction function of load l
$lc(c, t, s, m)$	Curtailable load c identifier at time t in scenario s in microgrid m
$PA_{l,t}$	Power access function of load l at time t
$p(g, t, s, m)$	Active power of generator g at time t in scenario s in microgrid m

$pcl(c, t, s, m)$	Amount of load c curtailment at time t in scenario s in microgrid m
$Ploss_i^w$	Active power losses of distribution network lines in (islanded or main) network w
$pchr(t, s, m)$	Charging power of battery at time t in scenario s in microgrid m
$pdcr(t, s, m)$	Discharging power of battery at time t in scenario s in microgrid m
$prdg(t, s, m)$	Power output of renewables (wind and solar) at time t in scenario s in microgrid m
$psell(t, m)$	Amount of active power sold by microgrid m at time t to distribution system
$pshf(t, s, m)$	Total load which is shifted to or from time t in scenario s in microgrid m
$pshed(t, s, m)$	Amount of load shedding at time t in scenario s in microgrid m
$pshift(t, t', s, m)$	Amount of load which is shifted from time t to time t' in scenario s in microgrid m
$Qloss_i^w$	Reactive power losses of distribution network lines in (islanded or main) network w at time t
$SOC(t, s, m)$	State of charge of battery at time t in scenario s in microgrid m
$u(g, t, s)$	Commitment status identifier of generator g at time t in scenario s
WA_l	Water access function of load l
WP_w	A binary variable which represents one or more water pumps are restored by network w
$x(l, t)$	Restoration status identifier of load l at time t
$y(g, t, s, m)$	Start-up identifier of generator g at time t in scenario s in microgrid m
$z(g, t, s, m)$	Shut-down identifier of generator g at time t in scenario s in microgrid m
$ I_{ij,t}^w $	Current magnitude between bus i and j at time t in (islanded or main) network w
$ V_{i,t}^w , V_{j,t}^w $	Voltage magnitude at bus i/j at time t in (islanded or main) network w
$\theta_{ij,t}^w$	Difference phase voltage angle between bus i and j at time t in (islanded or main) network w
$\Delta WA_{l,t}^{WP_w}$	Water accessibility improvement of load l at time t due to water pump(s) restoration by network w

1. INTRODUCTION

The use of energy is woven into the fabric of our cities and society. However, energy sector is vulnerable to natural disasters implying that a short time dysfunction in energy sector could result in subsequent worse events. The frequency of natural disasters occurrence has increased. In the U.S., between 2008-2012, power outages due to bad weather conditions cause the annual damage cost between \$25 billion and \$70 billion. For instance, the economic losses only from Hurricane Sandy in the U.S. were \$14–26 billion. To mention another case, 82 % of all buildings in Ha’apai Islands of Tonga were destroyed due to the 2014 Tropical Cyclone with a wind gust of 287 km/h [1]. According to [2], during natural disasters, about 90 % of the faults occur in electrical distribution networks. In that sense, a more resilient electrical network is strongly needed.

Electricity and power networks have important role in the operation of other infrastructures such as water and telecommunication. Power network outages can interrupt or stop the operation of these networks. For example, power outages due to hurricane caused shortage of clean water in New York City [3]. Power outages due to Earthquake in Christchurch in 2011, caused interruption in telecommunication network operation [4].

There are many definitions for resilience. One of the most acquisitive definitions according to the National Academy of Science, is that resilience is “*the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*” [5]. A system is considered to be absorptive if it can automatically absorb the effects of destructive events and minimize the consequences with minimal efforts. On the other hand, reaction and recovery of the system in minimum time is called the recoverability of the system. Moreover, the adaptive capacity is refers to the ability of the system to organize its components in a targeted manner with self-organization and learning mechanism [6]. In this sense, a resilient power system must have a high ability to restore the network with a fast response against several line outages [7]. Low-probability but high-impact are the properties of these faults such as those due to the natural disasters. The resilience of electrical power systems can be increased with various strategies. For instance, hardening, defined as physical changes in the network infrastructure to make it more resistant to extreme events, is one of the common but expensive strategies to increase resilience [8]. Another solution to enhance the resilience of the electrical distribution system is automation. Distribution system operates rapidly with utilization of different devices, such as remote fault indicators to decrease the fault detection time and remote control switches to decrease the open/close times of switches [9]. Distributed generations (DGs) are other options to increase the resilience of distribution systems after natural disasters. In [10], a microgrid is formed by a DG to restore critical loads. Unlike [10], in [11] multiple DGs can form a microgrid. Advanced monitoring, self-healing and demand response (DR) are other strategies that can enhance the resilience of power networks [12].

Microgrids can also enhance the resilience of distribution networks. These small power networks which can be operated in islanded or grid-connected mode include renewable energies, dispatchable generators and energy storages. According to [13], the Sendai microgrid that is a real microgrid survived for two days in islanded mode during the 2011 earthquake and tsunami in Japan. Li *et al.* [14] implemented microgrids with specified active and reactive power for load restoration in distribution systems. In [15], a new concept as Continues Operating Time (COT) is introduced to determine the maximum time that a microgrid can supply electricity to critical loads. In [15], a two-stage heuristic approach is implemented to solve the problem. In the first stage, a strategy table including the different feasible restoration paths is built, and the best path is determined thereafter using integer linear programming. In [16], the stability of microgrids is also considered when they are utilized to restore the critical loads. According to [17], the availability of microgrids during and after natural disasters can be affected by the lifeline of DGs and local battery. Markov state space model and cut-set theory are used in [17] to calculate the continuous availability of microgrids. In

addition to the information presented in [17], more parameters such as existing diesel generators, transportation time of fuel, microgrid architecture and power electronic interfaces are considered in [18] to quantify microgrid availability during natural disasters with Markov chains models.

With rapid expansion of microgrids in distribution network, there is an opportunity to enhance the resilience of distribution network with an appropriate framework. This framework should be attractive for both microgrids and distribution system operators to interact actively toward making a more resilient network. However, there are a number of challenges in setting up such an interactive framework. The first challenge is to implement a system-wide energy management system (EMS) for operation management of the network during different working conditions. EMSs that are designed for microgrid operation in emergency situations only try to improve the resiliency of the microgrid regardless of the system condition. Examples of such systems can be found in [19-21] where EMSs are designed exclusively for microgrids operation in islanded mode.

The second challenge is to provide robust communication between distribution network and microgrids. Natural disasters can damage the communication infrastructure, so it is essential that the number of communication links and the amount of data exchanged between the distribution network and the microgrids be in the minimum level.

The third challenge is to make an elastic load-supply balance within the whole system. In case of natural disasters, forced outage rate of generating units or distribution lines increases which in turn decreases the total primary energy supply. To handle this, DR actions can be effectively applied to change the normal electricity consumption through price-based or incentive-based mechanisms not only to meet the power balance, but also to achieve other goals [22]. These goals may include cost reduction in energy management of network microgrids [23, 24], voltage control [25], frequency regulation [26] and reliability enhancement [27]. Unlike fixed loads, only shiftable and curtailable loads can participate in DR programs [28].

In light of the reviewed literature, it can be clearly observed that although the number of research works in resilience improvement of power systems has been increased in recent years, there are still remaining issues in this field, especially when it comes to integrated energy systems. As an example, the research works in [14-16] are mainly focused on microgrids implementation to restore the loads only in power distribution network (PDN) from a distribution system operator's (DSO's) perspective. These approaches are not efficient in an integrated framework where power-water networks coexist and privately-owned entities (such as microgrids) should interact with DSO. Likewise, the proposed structures in [17-21] which mainly address the use of microgrids for service restoration during

extreme events, suffer from lack of efficient EMSs to determine how an interaction (in terms of energy exchange levels, pricing schemes and times of delivery) between the distribution network and microgrids can be formed. The important point is that how to design the mentioned EMS considering the owners of the microgrids? In other words, the interaction of microgrids and DSO will be different when the microgrids are owned by private entities or DSO. In our previous work [29], the mentioned EMS is designed for the microgrids that are owned by the DSO. On the other hand, although the contribution of demand-side resources (such as DR actions) in efficient energy scheduling of distribution networks are investigated in [23-28], the influence of responsive loads on resilience improvement of distribution systems is not taken into account. Regarding an integrated framework, the research work in [30] only considers the dependency of water network on power network and the potentials for water network damages are neglected.

This study proposes an efficient framework to improve the resilience of power-water distribution networks with privately-owned microgrids where interaction among different system operators are captured. The proposed framework is efficient for natural disasters such as hurricanes and floods when both PDN and water distribution network (WDN) can be damaged.

Compared to the existing literature, the novelty and contributions of this paper can be summarized as follow:

- An efficient interactive framework between distribution network and regional network of microgrids is proposed to enhance the resilience of an integrated electricity and water system. With the proposed framework, the microgrids with private owners can exchange energy with DSO during emergency period not only to make profit, but also to contribute to resilience improvement of the entire system,
- A flexible resilience-oriented scheduling scheme is proposed to help DSOs to restore the loads including disconnected water pumps with considering different parameters such as water consumption pattern and damages of WDN,
- Local loads reliability together with uncertainty associated with fuel arrival times are considered in the energy management of microgrids,
- The impact of responsive load contributions, energy storage sizing and fuel availability in microgrids on the distribution system resiliency is investigated.

The rest of this paper is organized as follows: Section 2 explains the proposed interactive framework. The problem formulation and solution methodology are provided in Section 3. Section 4 presents the simulation results. Finally, Section 5 concludes this paper.

2. PROPOSED INTERACTIVE FRAMEWORK

A. Natural disasters' impact on PDN and WDN

When a natural disaster such as hurricane or flood occurs, all elements in PDN and WDN are exposed to damages. The most vulnerable components in PDN and WDN are power poles, conductors and water pipes. In case of hurricanes, unlike the floods, the undergrounded water pipes will not be damaged. So, the major reason of loads inaccessibility to water will be introduced by the dependency of water pumps on electricity. However, to understand the vulnerability of an element to flood or hurricane, it is vital to identify the fragility function of each component. Fragility function is the probability of failure of a structure vs. the severity of a hazard such as wind speed or accumulated rain intensity [31]. The fragility function of PDN poles (pf_{pole}) and conductors ($pf_{conductor}$) against hurricane can be considered as below [32, 33]:

$$pf_{pole}(ws) = \Phi[\ln((ws) / m_R) / \xi_R] \quad (1)$$

where $\Phi[.]$ is lognormal cumulative distribution function with mean and standard deviation m_R and ξ_R , respectively which they depend on the structure of the pole. ws is the wind speed.

$$pf_{conductor}(ws) = \begin{cases} 0, & ws \leq ws_{\min} \\ \frac{ws - ws_{\min}}{ws_{\max} - ws_{\min}}, & ws_{\min} \leq ws \leq ws_{\max} \\ 1, & ws \geq ws_{\max} \end{cases} \quad (2)$$

Regarding the flood event and similar to [31], it is assumed that all power lines and water pipelines located in the flooding path will be damaged with a probability which will be obtained based on equation (1). It should be noticed instead of wind speed in equation (1), the rain intensity will be used. Furthermore, the parameters of m_R and ξ_R will be different for a power pole when it is used against flood or hurricane.

B. Framework of the integrated energy system

In Fig. 1, a power distribution system with a number of connected microgrids together with the water distribution network over the same geographical region is depicted. According to water network in Fig. 1, it is assumed that the water demand can be met through two pumps, which are fed electrically by the power distribution system. However, to understand the water pressure at different nodes of the system in different operation states of water pumps, it is essential to analyze the energy management network. In this regard, a water distribution system modeling software package (EPANET) is utilized to facilitate the process with a high precision.

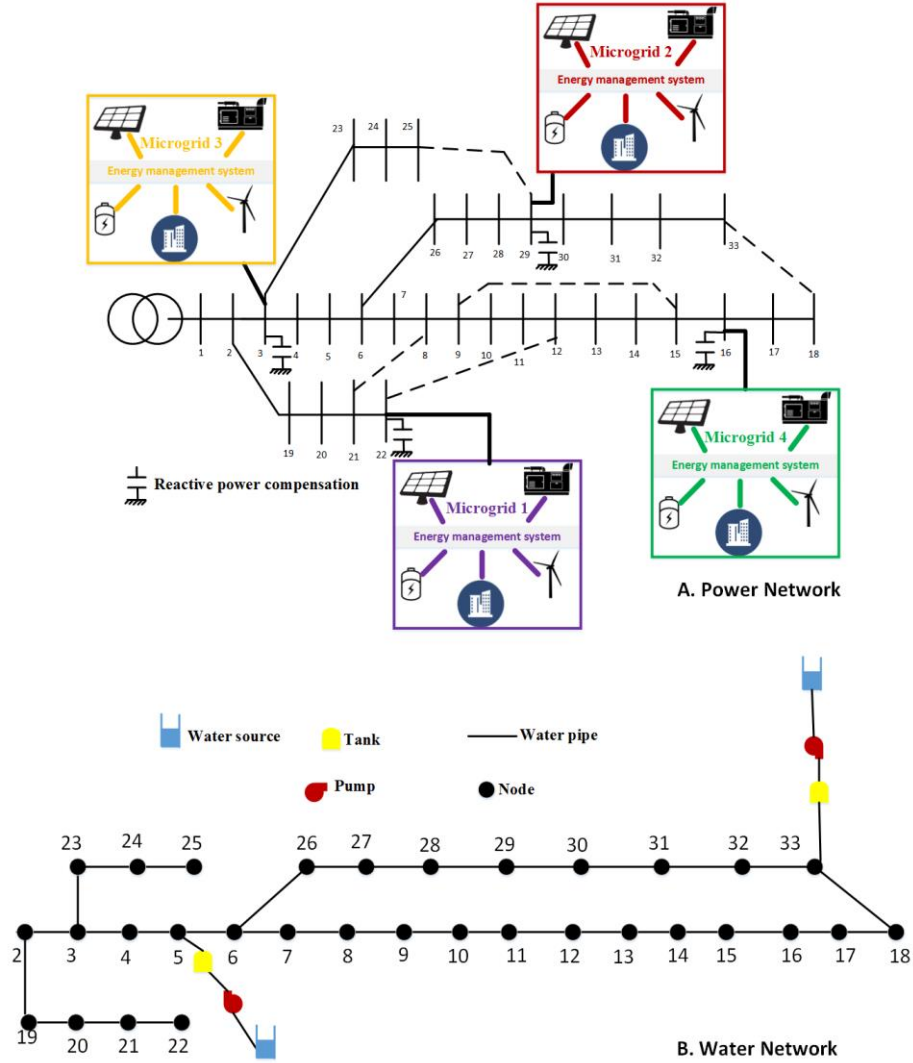


Fig. 1: Power distribution network with connected microgrids and related designed water network

In case of a natural disaster in the examined integrated energy system, several faults may occur and subsequently an emergency condition could be triggered denoting a power failure or a blackout. According to the interactive framework depicted in Fig .2, the distribution system operator (DSO) initially asks the microgrids to support the network by

restoring disconnected areas. To this end, it is necessary for DSO to send some information to the microgrids. One of the most important pieces of data is the estimated time required to locate and repair the faulty parts and to restore the distribution network to its normal state, i.e. the duration of emergency period. This duration is also deemed as the time interval in which microgrids switch from normal energy management strategy to the proposed strategy detailed in Section 2.C. In this paper, it is assumed that microgrids only provide active power for distribution network and required reactive power for loads restoration is locally generated by reactive compensations in the distribution network as Fig. 1. So the EMS for microgrids only schedules the active power. But, the restoration problem for DSO includes both active and reactive powers.

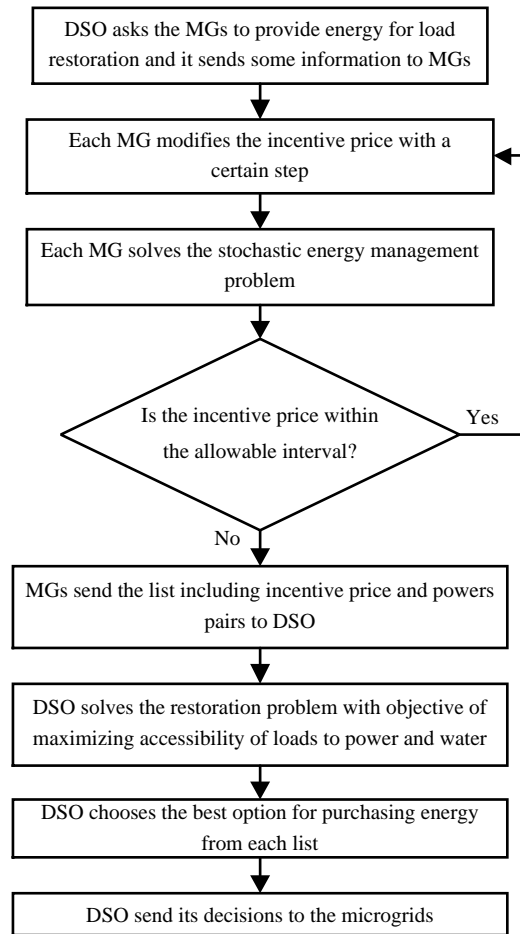


Fig. 2: The proposed interactive framework between distribution network and microgrids

The power provided by the microgrids to the distribution system must be available during the whole emergency period at the required quality. Moreover, the energy sold by the microgrid in different hours of the emergency period must be proportional to the amount of restored load. However, as the aggregated load profile often vary with a specific

coefficient at different hours, microgrids must be informed about the demand load at each interval of the emergency period by the distribution system operator. Having received such information, the microgrids solve their stochastic energy management problem and determine the bids and the amount of energy blocks to be sold in each interval of the examined period. Subsequently, DSO solves the restoration problem with the objective of maximizing the accessibility of loads to the power and the water and chooses the best option by considering the value of disconnected loads.

C. Proposed stochastic energy management system

The proposed EMS for each microgrid is formulated as a stochastic problem in which decisions are made through a scenarios set. The decision variables include *here-and-now* (which are made before the realization of the stochastic process) and *wait-and-see* (which are made after the realization of the stochastic process) [34]. In this paper, the amount of active power sold is *here-and-now* decision variables and the others, such as dispatchable generators power output are *wait-and-see* variables.

Two major classes of uncertainties including demand/renewable generation prediction and fuel arrival time are addressed by the EMS.

In the first step, numerous scenarios are produced for the first uncertainty category with the probability distribution function of each variable such as load profile, wind speed, and solar irradiance. In order to reduce the number of available scenarios to a tractable set, a well-known algorithm called backward reduction technique is utilized. It reduces the scenarios into a predefined number based on the Kantorovich distance [35]. The uncertainty of fuel arrival time is represented via an appropriate scenario set, which can be extracted from historical data. Thus, with a total number of N scenarios for representing the uncertainties of consumption load and renewable generation, and T scenarios for modelling the fuel arrival time, a total number of $N \times T$ scenarios should be considered for stochastic programming.

3. PROBLEM FORMULATION

In this section, the proposed interactive framework including stochastic EMS for microgrids and the restoration problem for distribution network are formulated.

A. Stochastic EMS for microgrids

Each microgrid is equipped with an EMS that manages the system performance considering the following goal:

$$\begin{aligned} \text{Min } & \sum_{s=1}^S \sum_{g=1}^G \sum_{t=t_0}^{T_c+t_0} pr(s) \left[u(g,t,s,m)A(g,m) + p(g,t,s,m)B(g,m) + \right. \\ & \left. y(g,t,s,m)SUC(g,m) + z(g,t,s,m)SDC(g,m) \right] + \\ & \sum_{s=1}^S \sum_{t=t_0}^{T_c+t_0} pr(s)pshed(t,s,m)VOLL(m) - \sum_{t=t_0}^{T_c+t_0} psell(t,m)(inprc(d) + \rho(t)) \quad m \in \{1,2,\dots,mg\}, d \in \{1,2,\dots,D\} \end{aligned} \quad (3)$$

In this objective function, the first line (i.e., terms in square bracket) indicates the operation, start-up, and shut-down costs of dispatchable generators. The second scenario-dependent term includes the cost of load shedding in the microgrid. This term considers the reliability of local microgrid loads. The third term indicates the profit made by selling energy to the distribution system. The incentive price is changed with an iterative algorithm in an allowable range (as stated in (4)) in each iteration.

$$\rho(t) \leq inprc(d) + \rho(t) < VOLL_m \quad t \in [t_0, t_0 + T_c], m \in \{1,2,\dots,mg\}, d \in \{1,2,\dots,D\} \quad (4)$$

The initial point for incentive price is the market price and in each iteration of the algorithm, a certain incentive step is added to the incentive price. With the new incentive price, the EMS is solved again. This algorithm is continued until the incentive price is less than the $VOLL_m$.

The constraints that must be satisfied in the stochastic EMS for each microgrid are expressed as follows.

$$pshf(t,s,m) = \sum_{t'=t_0}^{t_0+T_c} [pshift(t',t,s,m) - pshift(t,t',s,m)] \quad t \in [t_0, t_0 + T_c], s \in \{1,2,\dots,S\}, m \in \{1,2,\dots,mg\}, t \neq t' \quad (5)$$

According to [28], equation (5) is related to the DR program, which determines the amount of load shifted from or to time t .

Power balance is shown in the following expression:

$$\begin{aligned} load(t,s,m) - \sum_{c=1}^{C_m} pcl(c,t,s,m) + pshf(t,s,m) - pshed(t,s,m) = & \sum_{g=1}^{G_m} p(g,t,s,m) - psell(t,m) + pdcr(t,s,m) \\ - pchr(t,s,m) + prdg(t,s,m) \quad t \in [t_0, t_0 + T_c], s \in \{1,2,\dots,S\}, m \in \{1,2,\dots,mg\} \end{aligned} \quad (6)$$

There are three categories of loads in a microgrid: 1) shiftable ($pshift$), 2) curtailable (pcl) and 3) fixed. If the generation is lower than the demand at some hours, and if the microgrid operator cannot solve this issue with shiftable and curtailable load, then some loads will be disconnected ($pshed$) to avoid system instability.

According to [19], the operation of dispatchable generators have some constraints. Active power of each generator should be limited in a range.

$$\begin{aligned} p^{\min}(g,m)u(g,t,s,m) \leq p(g,t,s,m) \leq p^{\max}(g,m)u(g,t,s,m) \\ g \in \{1,2,\dots,G_m\}, t \in [t_0, t_0 + T_c], s \in \{1,2,\dots,S\}, m \in \{1,2,\dots,mg\} \end{aligned} \quad (7)$$

Ramp-up and ramp-down of each generator are limited by the following expressions:

$$p(g, t, s, m) - p(g, t-1, s, m) \leq R^{DN}(g, m) \quad g \in \{1, 2, \dots, G_m\}, t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (8)$$

$$p(g, t-1, s, m) - p(g, t, s, m) \leq R^{UP}(g, m) \quad g \in \{1, 2, \dots, G_m\}, t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (9)$$

The constraints related to the start-up and shut-down of each generator are expressed as follows:

$$y(g, t, s, m) - z(g, t, s, m) = u(g, t, s, m) - u(g, t-1, s, m) \\ g \in \{1, 2, \dots, G_m\}, t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (10)$$

$$y(g, t, s, m) + z(g, t, s, m) - 1 \leq 0 \quad g \in \{1, 2, \dots, G_m\}, t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (11)$$

The capacity of the connection link between the microgrid and the distribution system is expressed by the following:

$$psell(t, m) \leq Cap^{\max}(m) \quad t \in [t_0, t_0 + T_c], m \in \{1, 2, \dots, mg\} \quad (12)$$

Battery operation constraints are determined by (13)-(16) [20, 24]. According to (13), the state of charge (SOC) of battery is limited in allowable range.

$$SOC_{\min}(m) \leq SOC(t, s, m) \leq SOC_{\max}(m) \quad t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (13)$$

Constraint (14) indicates the relationship between the SOC and charging/discharging rates.

$$SOC(t, s, m) = SOC(t-1, s, m) + pchr(t, s, m)\eta(m) - \frac{pdcr(t, s, m)}{\eta(m)} \\ t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (14)$$

Charging/discharging rates of battery are expressed as constraints (15)-(16).

$$\begin{cases} 0 \leq pchr(t, s, m) \leq \frac{(SOC_{\max}(m) - SOC(t-1, s, m))}{\eta(m)} \\ pchr(t, s, m) \leq pchr_{\max} \end{cases} \quad t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (15)$$

$$\begin{cases} 0 \leq pdcr(t, s, m) \leq (SOC(t-1, s, m) - SOC_{\min}(m))\eta(m) \\ pdcr(t, s, m) \leq pdcr_{\max} \end{cases} \quad t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (16)$$

According to [28], some loads in each microgrid are allowed to be curtailed in the DR program at certain hours as constraints (17)-(18).

$$pcl(c, t, s, m) \leq lc(c, t, s, m)load_{cur}^{\max}(c, m) \quad c \in \{1, 2, \dots, C_m\}, t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (17)$$

$$\sum_{t'=t_0}^{T+t_0} lc(c, t', s, m) \leq Tload_{cur}^{\max}(c, m) \quad c \in \{1, 2, \dots, C_m\}, t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (18)$$

Constraint (19) indicates the maximum amount of loads that can be shifted from hour t to other hours.

$$\sum_{t'=t_0}^{T+t_0} pshift(t, t', s, m) \leq load_{shift}^{\max}(m) \quad t \in [t_0, t_0 + T_c], s \in \{1, 2, \dots, S\}, m \in \{1, 2, \dots, mg\} \quad (19)$$

Constraint (20) express the limitation of fuel capacity in each microgrid. This constraint indicates that the available fuel capacity for a generator is considered as a determined amount of energy can produce.

$$\sum_{t=t_0}^{t_0+FAT(s,m)} p(g,t,s,m) \leq Fuel_{cap}^{avial}(m) \quad g \in \{1,2,...,G_m\}, t \in [t_0, t_0 + T_c], s \in \{1,2,...,S\}, m \in \{1,2,...,mg\} \quad (20)$$

According to (21) and as mentioned before, each microgrid should sell power to the DSO proportional to the load variation in the distribution network. In this paper, it is assumed that the restoration plan will be performed only for one time due to hard conditions after occurrence of natural disasters. According to this assumption, if a load is chosen to be restored, it must be fed in the entire emergency period. Therefore the energies sold to the DSO by the microgrids should be proportional to the load variation of the power distribution network. In other words, the goal is to restore the important loads such as water pumps in the whole emergency period. For example, if a microgrid sells energy as amount of 200 kWh at t_1 and 5 kWh at t_2 to the DSO, the DSO should restore a lot of loads ignoring their importance at t_1 and maybe the DSO cannot restore any important load at t_2 . This condition is not efficient in the resilience improvement of the networks. In other words, the proposed EMS not only consider the profit of the microgrids but also consider the resilience improvement of distribution networks.

$$psell(t,m) = lf(t)psell(t_h,m) \quad t \in [t_0, t_0 + T_c], m \in \{1,2,...,mg\} \quad (21)$$

where $lf(t)$ is the load variation profile in the emergency period which is normalized based on the lowest demand load at hour t_h in the examined period and is reported by the DSO to the microgrid.

The proposed EMS is a stochastic linear program that can be solved by any related solution algorithms or solvers such as CPLEX.

B. Distribution network service restoration

Having received the bids and the amount of energy blocks from the microgrids, DSO must restore the disconnected loads with the aid of microgrids through appropriate partitioning of the system. According to [30], a function (named as load satisfaction function (LSF)) is defined for each load which indicates the accessibility of that load to power and water:

$$LSF_i = \gamma_i PA_i + \mu_i WA_i \quad (22)$$

γ_i and μ_i are weighting factors defined for each load such that $\gamma_i + \mu_i = 1$. PA is a binary variable that indicates the state of loads in the power distribution system.

$$PA = \begin{cases} 1 & \text{if load is connected} \\ 0 & \text{if load is disconnected} \end{cases} \quad (23)$$

WA is the accessibility function of loads to water. In other words, WA indicates the satisfaction level of loads access to water after natural disasters. Accessibility of a load to water is proportional to the water pressure in the node which that load is located.

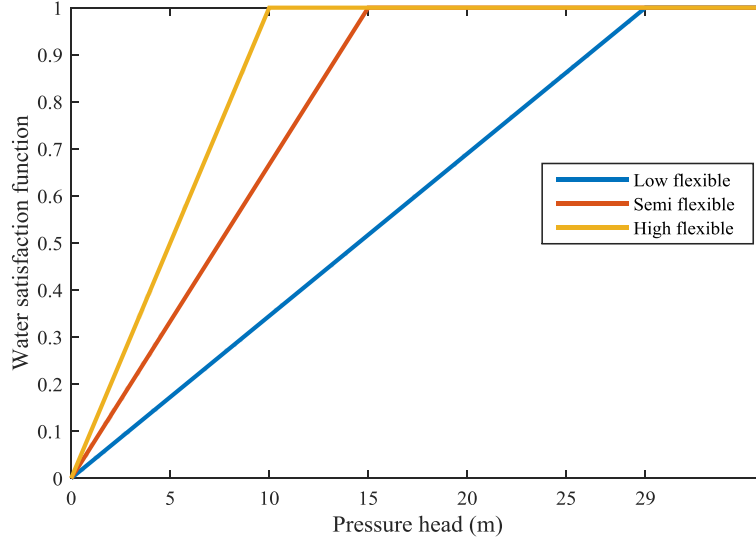


Fig. 3: Water pressure satisfaction function

According to Fig. 3, in this paper, three kinds of water satisfaction functions (WSF) is defined for users. According to the low-flexible curve, the minimum required water pressure head in nodes is 29 m which is reported in many researches. This value is given for the water network operation in normal conditions. But in emergency conditions due to natural disasters, the expected satisfaction level of accessibility of loads to water will be decreased. To this end, two other curves with less required minimum pressure are proposed. The impact of all of curves on the restoration of water pumps will be evaluated. The value of weighting factors in LSF for each load is in range of 0 to 1. For residential and commercial loads γ and μ are assumed to be 0.5, 0.5 and 0.9, 0.1, respectively. With this model, the objective function of restoration is to maximize the accessibility of loads to both power and water:

$$\text{Maximize } \sum_{i=1}^{N_l} LI_i LSF_i \quad (24)$$

The DSO can restore the disconnected loads with two possible actions: 1) Reconfiguration of the distribution network to reroute the power while the utility as a power source still supports the system, and 2) Intentional islanding of a microgrid or cluster of microgrids to support local loads.

In each time interval and for each network (main or islanded), the following load flow equations and constraints must also be satisfied. Real/reactive power balance at each bus, line current and bus voltage limitation are addressed by (25)-(28).

$$P_{i,t}^w = |V_{i,t}^w| \sum_j |V_{j,t}^w| (G_{ij} \cos \theta_{ij,t}^w + B_{ij} \sin \theta_{ij,t}^w) \quad i \in \{1, 2, \dots, N_w\}, t \in [t_0, t_0 + T_c], w \in \{1, 2, \dots, W\} \quad (25)$$

$$Q_{i,t}^w = |V_{i,t}^w| \sum_j |V_{j,t}^w| (G_{ij} \sin \theta_{ij,t}^w - B_{ij} \cos \theta_{ij,t}^w) \quad i \in \{1, 2, \dots, N_w\}, t \in [t_0, t_0 + T_c], w \in \{1, 2, \dots, W\} \quad (26)$$

$$|V_{\min}| \leq |V_{i,t}^w| \leq |V_{\max}| \quad i \in \{1, 2, \dots, N_w\}, t \in [t_0, t_0 + T_c], w \in \{1, 2, \dots, W\} \quad (27)$$

$$|I_{ij,t}^w| \leq |I_{ij}^{\max}| \quad i \in \{1, 2, \dots, N_w\}, t \in [t_0, t_0 + T_c], w \in \{1, 2, \dots, W\} \quad (28)$$

Constraint (29) guaranties the radial topology of the main network or each islanded microgrid. It should be noticed, this constraint is checked for the networks which are connected graphs.

$$N_b^w = N_{line}^w + 1 \quad w \in \{1, 2, \dots, W\} \quad (29)$$

Furthermore, the following constraints must be satisfied for each islanded network which is supplied by one or more microgrids. According to (30), the total demanded active power of the loads plus the active power losses of distribution lines within each islanded network should not exceed the contracted power between the microgrid(s) (which supply the islanded network) and the DSO. The same should be satisfied for reactive power as shown in (31).

$$\sum_{l=1}^{N_l^w} P_{l,t}^w + P_{loss_t}^w \leq \sum_{m=1}^{N_{mg}^w} p_{sell}(t, m) \quad t \in [t_0, t_0 + T_c], w \in \{1, 2, \dots, W-1\} \quad (30)$$

$$\sum_{l=1}^{N_l^w} Q_{l,t}^w + Q_{loss_t}^w \leq \sum_{i=1}^{N_k^w} Q_i^{resource} \quad t \in [t_0, t_0 + T_c], w \in \{1, 2, \dots, W-1\} \quad (31)$$

The DSO must purchase power from microgrids considering a budget limit as shown in (32). It is noteworthy that *CVLIP*, *FVLIW* of each load is related to the load type and demand level.

$$\sum_{t=t_0}^{T_c+t_0} \left[\sum_{l=1}^{N_l^w} [PA_{l,t} CVLIP_{l,t}] + WP_w \sum_{l=1}^N \Delta WA_{l,t}^{WP_w} FVLIW_{l,t} \right] \geq \sum_{m=1}^{mg_w} \sum_{t=t_0}^{T_c+t_0} p_{sell}(t, m) (inprc^{win}(m) + \rho(t)) \quad w \in \{1, 2, \dots, W-1\} \quad (32)$$

After natural disasters and lines outage in the distribution network, there are two possible states for each microgrid in the new configuration of distribution network. In the first state, it is still located in the main network that is supplied by the utility. In the second state, it is located in an isolated network such that the microgrid is responsible for load

restoration. In this paper, *Modified Viterbi algorithm* is used for service restoration. This method is comprehensively explained and discussed in [30].

In the first state, DSO only purchases power from the microgrids if service restoration requires load shedding. Furthermore, note that load shedding may be needed to be performed in some intervals of the emergency period, so that the DSO requests power purchasing only in desired time intervals from the microgrids. In order to achieve this, it is only necessary to announce the load variation factor ($lf(t)$) in the desired interval to the microgrid. In other words, during other intervals of the emergency period, $lf(t)$ is zero.

In the second state, the DSO must purchase power to restore the loads in the isolated network thorough the entire emergency period. This process is accomplished through two steps. At the first step, all the network nodes (loads combinations) that can be fed by each microgrid and satisfy constraints (25)-(29) are sorted based on their related costs (i.e., objective function (24)). At the second step, the DSO can realize which of the offered bid-quantity energy blocks by each microgrid is feasible and appropriate to purchase from both technical and economic perspective.

4. SIMULATION RESULTS

The modified IEEE 33 bus distribution network with connected microgrids and its related designed water network as shown in Fig. 1 is studied to illustrate the effectiveness of the proposed method. Two different types of microgrids are considered that each one has a specified generation mix and demand level. It is assumed that two microgrids in nodes 16 and 22 are microgrids type 1 and the others (microgrids in nodes 3 and 29) are microgrids type 2. The parameters of three dispatchable generators which are obtained from [20] are shown in Table. 1. According to Table 1, microgrids of type 1 has three dispatchable generators which are No. 1, No. 2 and No. 3 while in microgrids of type 2, there is only one generator of type No.3. Dispatchable generators can increase or decrease their full capacities in less than one minutes.

Table 1: Dispatchable generators parameters in microgrid

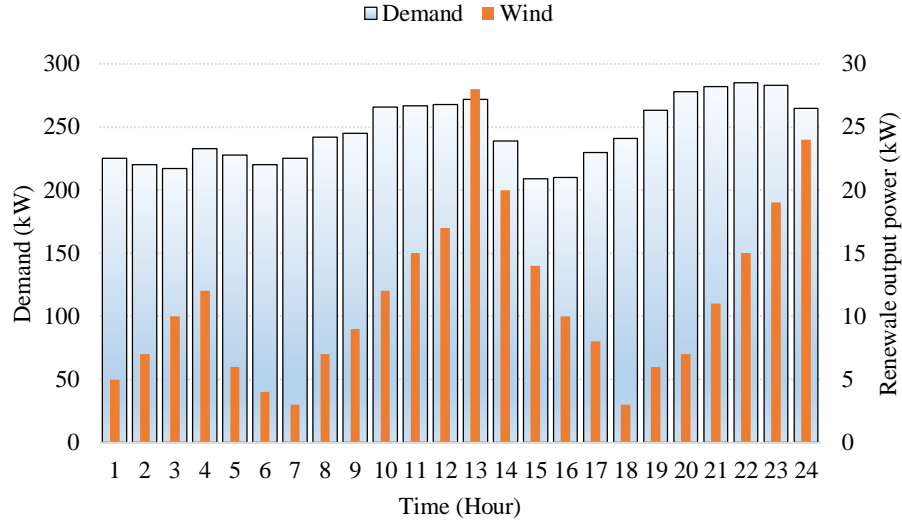
No.	p_g^{\min}	p_g^{\max}	A_g	B_g	SUC_g	SDC_g
	(kW)	(kW)	(\$)	(\$/kWh)	(\$)	(\$)
1	0	78	2.552	0.029	0.09	0.08
2	0	84	2.552	0.028	0.16	0.09
3	0	98	0.851	0.043	0.12	0.08

The maximum fuel available for each generator is equal to the production of 400 kWh of energy. The required data for the battery which is available in both types of microgrids is summarized in Table 2.

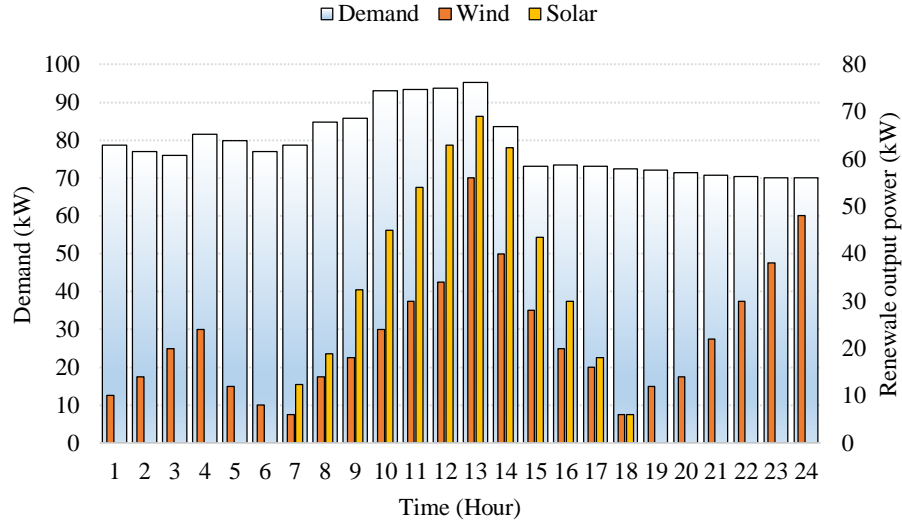
Capacity (kWh)	Maximum rate of Charging/Discharging Power (kW)	Min-Max SOC (kWh)	Initial SOC (kWh)	η
200	70-100	0-200	50%=100	0.95

The hourly load profile, wind power and solar power generation for different types of microgrids are depicted in Fig.

4.



(A)



(B)

Fig. 4: Hourly demand, wind power and solar power profiles in microgrids: A) Type-1 microgrid B) Type-2 microgrid

In both types of microgrids, the loads are categorized into fixed, shiftable and curtailable loads, while the value of lost load is considered as 5 \$/kWh. It is assumed that 80% of hourly loads are fixed and 10 % are shiftable. The remaining

loads are divided into three groups of curtailable loads with amounts of 5%, 3%, and 2 % of the hourly load. Each of these load groups can be curtailed for two hours during the emergency period. The maximum PCC power exchange of each microgrid to distribution network is 200 kW. The market price is based on a time-of-use (TOU) scheme that is given in Table. 3.

Table 3: Energy price based on TOU tariff			
Time	Off-peak (1:00-7:00, 23:00-24:00)	Shoulder (8:00-14:00)	Peak (15:00-22:00)
Price (\$/kWh)	0.07	0.09	0.11

The initial incentive price is equal to 0 \$/kWh. The incentive step that is added to the incentive price in each iteration is 0.5 \$/kWh. Two types of uncertainties in the proposed stochastic EMS for microgrids should be addressed. For the first type of uncertainties including demand and renewable generation output, each microgrid produces 2000 scenarios initially based on a normal distribution function with 3% , 5% and 5% error in demand, wind power and solar power predictions, respectively. Then, 10 scenarios are chosen with the backward reduction algorithm. To address the second type of uncertainty including fuel arrival time, it is assumed that the minimum time of fuel delivery to both types of microgrid is 4 hours and five scenarios with different probabilities are shown in Table 4.

Table 4: Different fuel time arrival scenarios					
Scenario including time of fuel delivery	4	5	6	7	≥ 8
Probability of each scenario	0.4	0.3	0.15	0.1	0.05

Finally, 50 scenarios with different probabilities are generated in order to solve the stochastic EMS by each microgrid. The active/reactive power in PDN and water demand in WDN are depicted in Fig. 5. It should be noticed loads in nodes 19-22 are commercial and the other are residential.

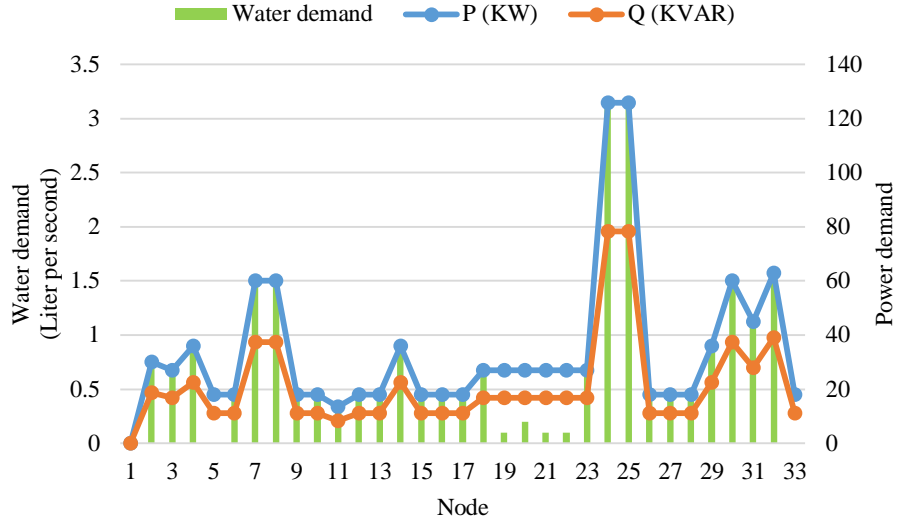


Fig. 5: Active power, reactive power demands of distribution network

Value of load inaccessibility to power and water is depicted in Fig. 6. For the nodes, which include water pumps, the value of load inaccessibility to power is considered as a dynamic value denoting the importance of each water pump for restoration phase. It should be noted that the importance of each water pump for restoration will be determined in the restoration problem by incorporating the WSF of loads resulted from EPANET. The 24-hour load multipliers of the PDN and WDN are illustrated in Fig. 7. Other information about the IEEE 33-bus distribution system can be found in [36].

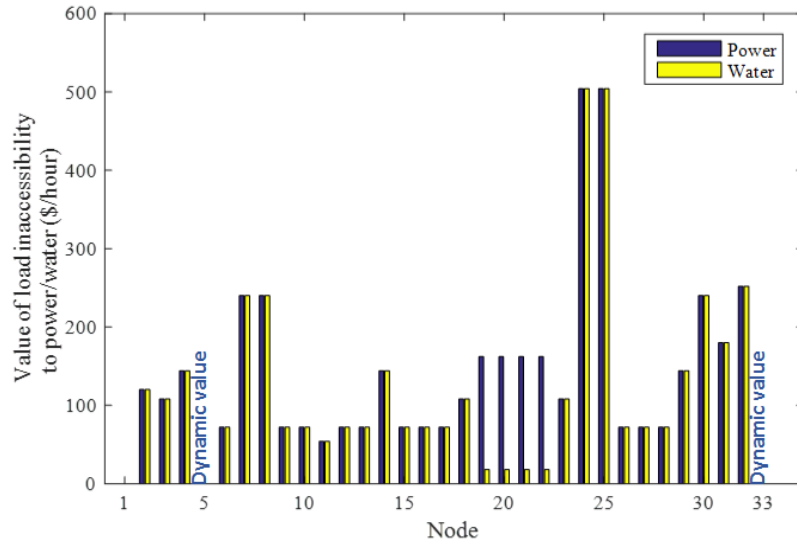


Fig. 6: Value of loss inaccessibility to power and water

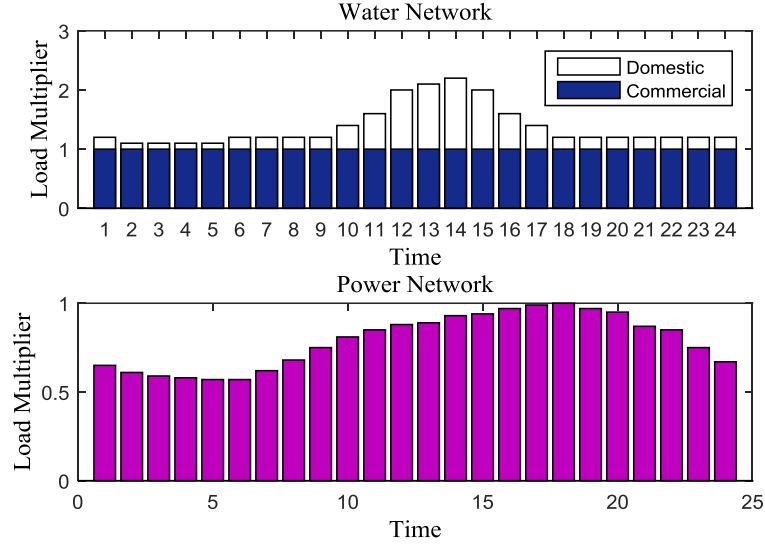
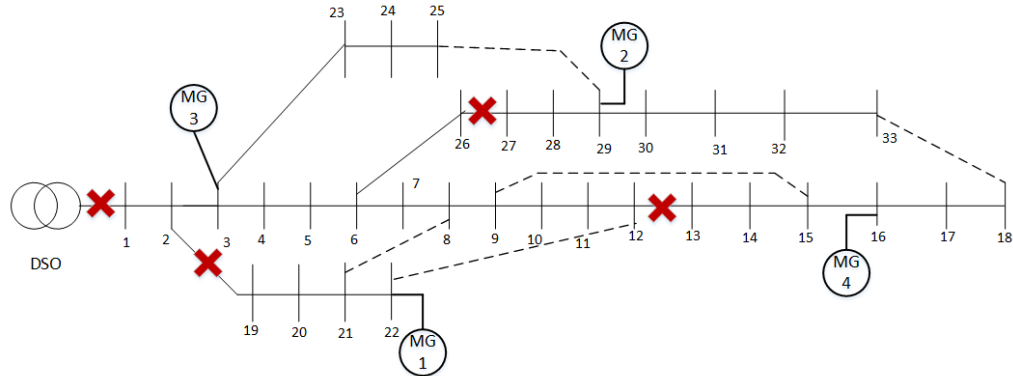


Fig. 7: Load multiplier of the distribution system

Case 1:

The proposed interaction framework is simulated with a harsh scenario due to hurricane which is depicted in Fig. 8. It is assumed that four faults have occurred at 9 A.M. in lines 12-13, 2-19, 26-27 and the one feeding from the transformer and the required time to repair the lines is 8 hours. As mentioned before, the under grounded water pipes will not be damaged due to hurricane. According to Fig. 9, all the nodes will access to water only for the first hour (9:00-10:00) of the emergency period due to water tanks in the water network (see Fig. 1) and there is no water access for the rest of emergency period (10:00-17:00). The only way to restore loads as much as possible is to enable the individual microgrids operation. Thus, the DSO asks microgrids for their contributions in system restoration and sends the required data as shown in Fig. 8 to the microgrids. Subsequently, the EMS in each microgrid provides the action plan.



Sending Data:
 Emergency period= 9 A.M- 16P.M.
 Load variation coefficient considering losses or $lf(t)$
Receiving Data: The list including amount of power and incentive price pairs.

Fig. 8: Schematic diagram of the distribution system with multiple microgrids during the faults

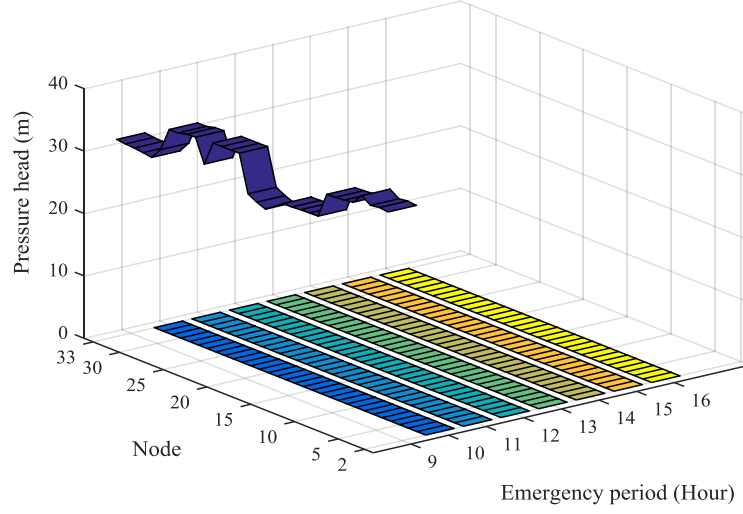


Fig. 9: Water accessibility of loads to water during emergency period before restoration

The action plans of microgrids type 1 (microgrids in nodes 16 and 22) and microgrids type 2 (microgrids in nodes 3 and 29) are shown in Fig. 10 and Fig. 11, respectively. Each plan includes the amount of active power and incentive price. As can be seen in Fig. (10) and Fig. (11), the energy sold by the microgrids increases as the incentive step increases and it depends on each microgrid scheduling. It is worth-mentioning that the price of each option in each action plan is determined based on the incentive step price plus the market price. All tests are performed on a PC with 2.5-GHz CPU and 4GB RAM. The required time for solving the stochastic EMS for microgrids type 1 and 2 is around 20-25 seconds.

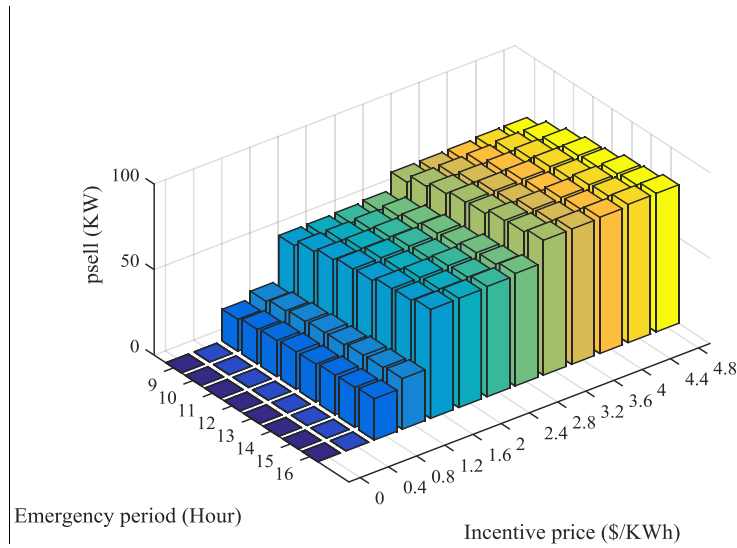


Fig. 10: Bid-quantity packages offered by microgrids type 1

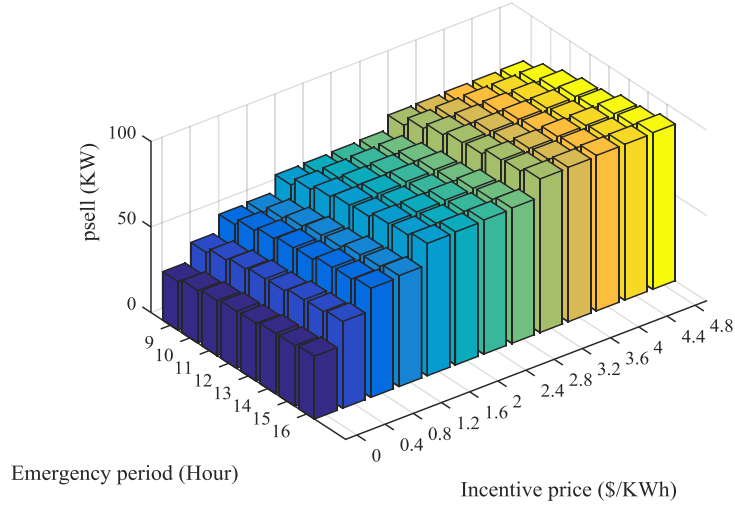


Fig. 11: Bid-quantity packages offered by microgrids type 2

Having received the bid-quantity lists from the microgrids, DSO solves the restoration problem. To analysis the impact of WSF on water pumps restoration, the restoration problem is solved with all the proposed curves as in Fig. 3. The results of the restoration problem is explained in Table. 5. The restoration problem takes about 5 seconds to be solved.

Table 5: Results of restoration problem with different WSF curves against hurricane

Items	WSF curve	Microgrid in node 3	Microgrid in node 16	Microgrid in node 22	Microgrid in node 29
Incentive price (\$/kWh)	Low flexible	2.4	2.8	2.8	1.6
	Semi flexible	2.4	2.8	2.8	1.6
	High flexible	2.4	3.2	2.8	1.6
Loads restored	Low flexible	3,4,5	16,17,18,33	20,21,22	27,28,29
	Semi flexible	3,4,5	16,17,18,33	20,21,22	27,28,29
	High flexible	3,4,5	14,15,16,17	20,21,22	27,28,29
Value of restored loads (both power and water) (\$)	Low flexible	21795.7	7898.3	3888	2304
	Semi flexible	26472	3222	3888	2304
	High flexible	27513.7	2880	3888	2304
Cost of purchasing energy from microgrid (\$)	Low flexible	1422.9	1656.8	1656.8	945
	Semi flexible	1422.6	1656.8	1656.8	945
	High flexible	1422.6	2140.2	1656.8	945

According to Table. 5, DSO can restore many loads with the aid of microgrids. Note that the values of loads, which are restored by the microgrids, are more than the cost of the power purchased by the microgrids. For example, DSO can restore loads 20-22 with microgrid in node 22. However, as load 19 is neighborhood to loads 20-22, but, this load is not restored. The reason is that the conditions in (30)-(32) cannot be met by any of the options in bid-quantity packages offered by microgrid in node 22 if load 19 is also added to the list of restored loads.

Regarding the water pump restoration, it can also be observed from Table 5 that pumps in nodes 5 and 33 are restored with microgrids in nodes 3 and 16, respectively considering low- and semi-flexible WSF curves. According to Fig .12, in this condition both pumps are restored and the water pressure of nodes is more than 29 m (minimum pressure required for normal operation).

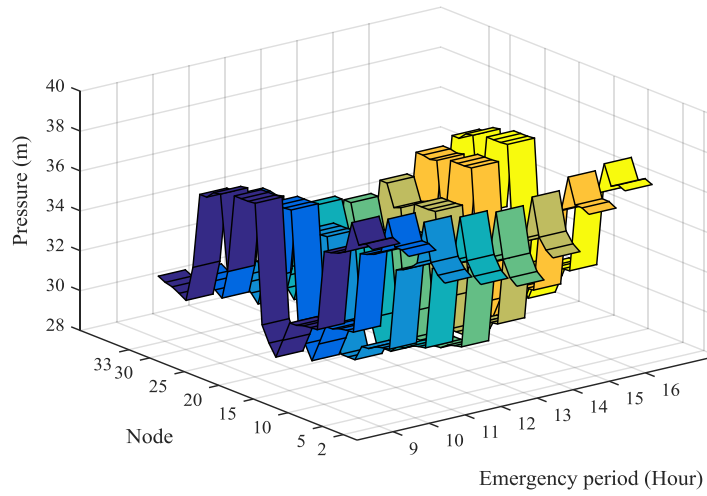


Fig. 12: Water pressure in nodes when both water pumps are restored

With high-flexile WSF curve, the optimal plan is achieved only by restoration of the more important water pump (which is the one in node 5). However, compared to the results obtained in cases with low- and semi- flexible WSF curves, it is clearly understood that loads 14 and 15 are restored (instead of loads in nodes 33 and 18) due to their higher load values. The water pressure in different nodes with the operation of water pump in node 5 is illustrated in Fig. 13.

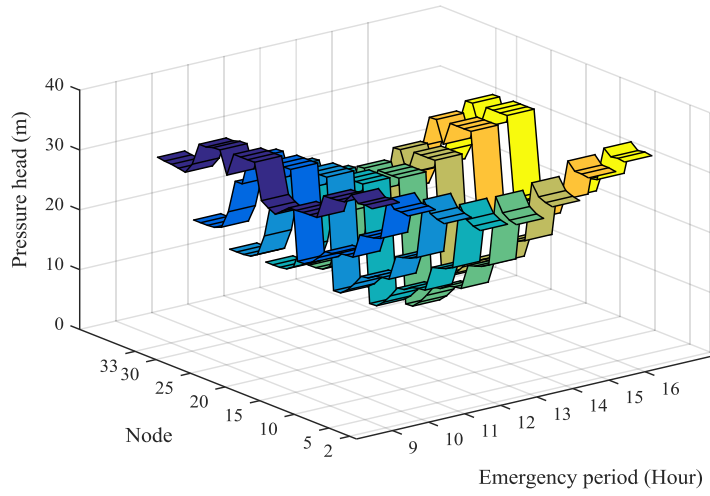


Fig. 13: Water pressure in nodes when only water pump in node 5 is restored

According to Table. 5, the value of the restored loads for microgrids that are not able to restore any water pumps in their electrification domain (e.g., microgrids in nodes 22 and 29), is only determined by the accessibility of nodes to power. On the other side, for the microgrids which can restore water pumps, the value of their restored loads would be determined by the accessibility of nodes to both power and water. It should be noticed, the value of loads accessibility to water will be different when different WSF curves are taken into account.

As it can be seen in Table. 5, moving from low to high-flexible curves, the value of restored loads for microgrid in node 3 which restores the water pump in node 5 is increased. The opposite trend is observed for microgrid in node 16 which is responsible for restoration of water pump in node 33 with low and semi-flexible curves. The reason is that, according to Fig. 13 and also the characteristics of low to high-flexible curves (i.e., the required pressure head for normal operation of water network), the contribution of water pump in node 33 in providing water is decreased as the other water pump could guarantee the adequacy of service. Such contribution could be even zero once high-flexible curve is taken into account which denotes a situation where water pump in node 33 is not restored.

To investigate the reliability of microgrids local loads in terms of expected energy not served (EENS), let's consider microgrids of type 2. According to Fig. 10, by increasing the incentive steps, the microgrid sells more power to the distribution system during the emergency period. At the same time, according to Fig. 14, EENS of the microgrid during the emergency period is increased, meaning that the reliability of microgrid loads has decreased. However,

with the increase of the incentive price, the EMS determines the sold power and the expect load shedding in such a way that the profit of the microgrid is maximized.

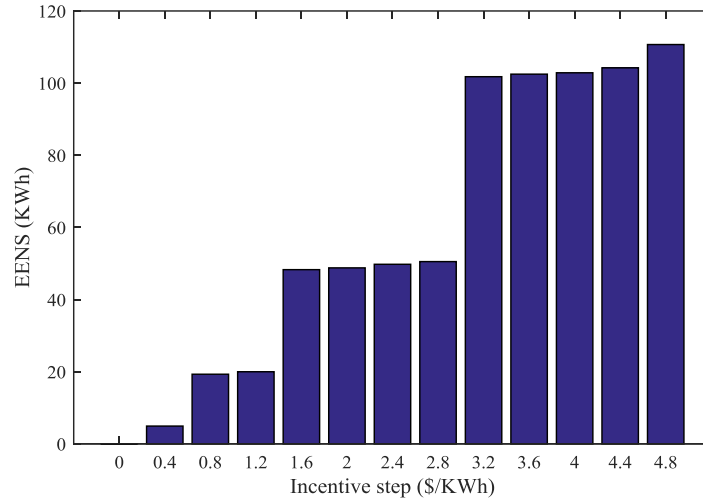


Fig. 14: Expected load shedding of the microgrid based on incentive steps during the emergency period

If the operator of a microgrid wants to operate the microgrid in a conservative approach. The operator can only report the options in the bid-quantity energy block which satisfy his/her desired reliability level of microgrid.

Case 2:

This case is investigating the efficiency of the proposed framework for enhancing the resilience of PDN and WDN vulnerable to flooding. The difference between this case and the previous one is that the flood, unlike the hurricane can also damage the pipes of the water network. According to Fig. 15, under a given flood scenario it is assumed that several power distribution lines (i.e, 3-23,6-26,9-15,12-22,9-10,10-11,11-12,12-13) and also water network pipes (i.e., 3-23,6-26,9-10,10-11,11-12,12-13) will be damaged.

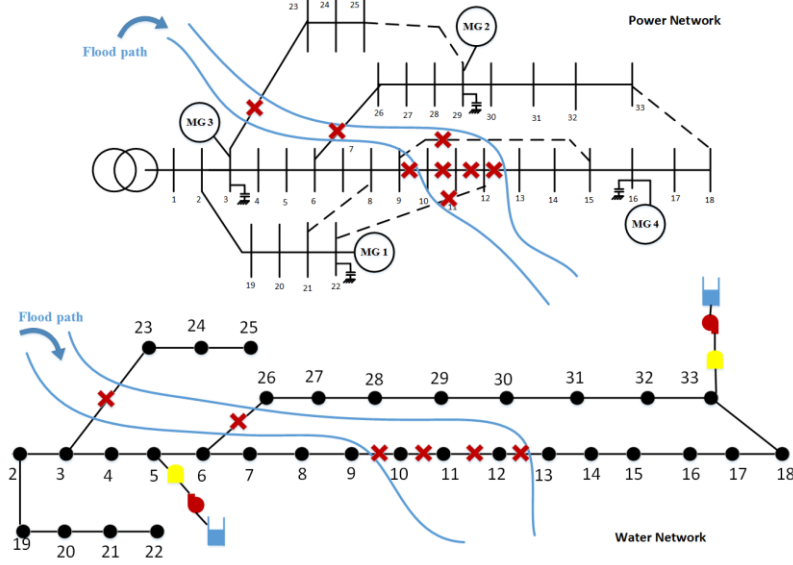


Fig. 15: Schematic diagram of the faulty sections in PDN and WDN during a flood event

Similar to Case 1, it is assumed that these faults have occurred at 9 A.M. due to flood. The required time to repair the power distribution lines and water pipelines is assumed to be 8 and 10 hours, respectively. As can be seen in Fig. 15, the flood causes a power outage over a wide region which includes nodes (10-18) and (23-33) in distribution network. To restore the disconnected nodes in neighboring areas, microgrids in nodes 16 and 29 could effectively be engaged in doing so. Due to the similarity of fault occurrence time and the required repair time of this case with case 1, the action plans of microgrids 16 and 29 would be similar to those in case 1, which are depicted in Figs 10 and 11. As can be seen in Fig. 15, due to the flooding, the WDN is divided into two islanded networks. Water pumps in node 5 and 33 could deliver water to nodes (2-9),(19-22) and (13-18),(26-33), respectively. However, other loads in faulty areas will be lost.

Having received the bid-quantity lists from the microgrids, DSO solves the restoration problem. The restoration plan is explained in Table. 6. Unlike case 1, the DSO prefers to restore node 33, which also included the water pump, in all different WSFs. The reason lies in a fact that the water pump in node 33 is responsible to deliver water to nodes (13-18) and (26-33), thus has a higher priority in restoration phase compared to other nodes in the network. This also indicates the efficiency of the proposed framework that can consider the impact of faults on water network as well. Figs. 16 and 17 compare the pressure head at the nodes in different state of water pump in node 33.

In Comparison with case 1, the DSO can restore one more node (i.e., node 26) due to the structure of the PDN. To do so, the DSO has to purchase more power with higher incentive prices compared to case 1 from microgrid in node 29.

Table 6: Results of restoration problem with different WSF curves against flood

Items	WSF curve	Microgrid in node 16	Microgrid in node 29
Incentive price (\$/kWh)	Low flexible	2.8	3.2
	Semi flexible	2.8	3.2
	High flexible	2.8	3.2
Loads restored	Low flexible	16,17,18,33	26,27,28,29
	Semi flexible	16,17,18,33	26,27,28,29
	High flexible	16,17,18,33	26,27,28,29
Value of restored loads (both power and water) (\$)	Low flexible	10396.7	2880
	Semi flexible	10749	2880
	High flexible	10907.2	2880
Cost of purchasing energy from microgrid (\$)	Low flexible	1656.8	2133.2
	Semi flexible	1656.8	2133.2
	High flexible	1656.8	2133.2

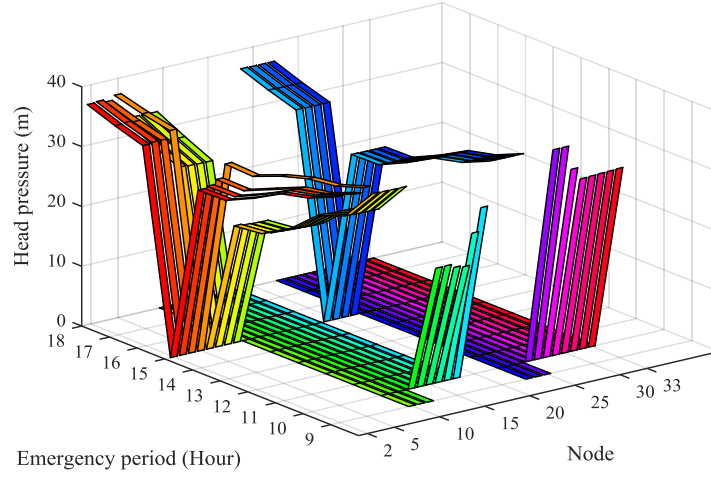


Fig. 16: Water pressure in nodes when water pump in node 33 is not restored

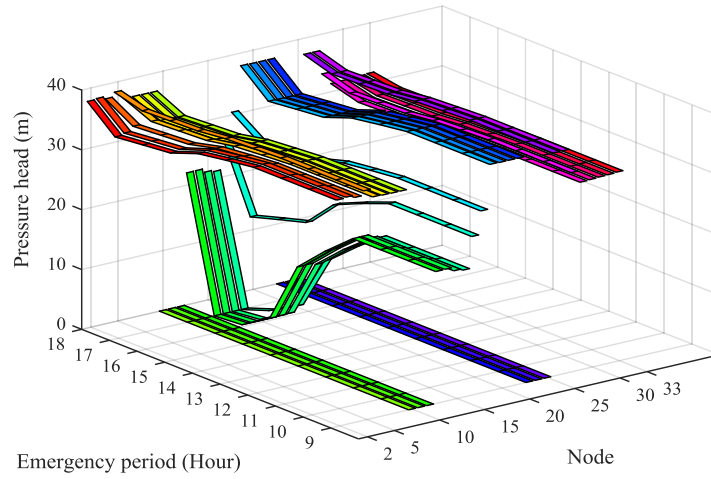


Fig. 17: Water pressure in nodes when water pump in node 33 is restored

Case 3:

In this case, the impact of DR on resilience improvement of distribution network is studied. During the emergency conditions, if the microgrids can provide more energy with lower prices, DSO will restore more loads which implies less EENS and increased resiliency. To this end, an index is proposed in (33) which indicates expected amount of provided energy per dollar for distribution network by microgrids. The higher this index, a microgrid can contribute more to the improvement of the distribution networks (i.e., selling more energy with lower prices).

$$EpD = \frac{1}{D} \sum_{d=1}^D \sum_{t=t_0}^{t_0+T_i} \frac{psell(d,t)}{(inprc(d) + \rho(t))} \quad (33)$$

To investigate the impact of DR program on this index, let's consider microgrids type 2. The EMS for microgrids type 2 for different combination of loads is run at 17 o'clock for 8 hours and EpD index is shown in Fig. 18. With increasing the DR actions, the EpD index increases, meaning that responsive loads could enhance the distribution network resilience. In particular, the curtailable loads are more efficient in providing energy with lower price for distribution network and can significantly increase the EpD index.

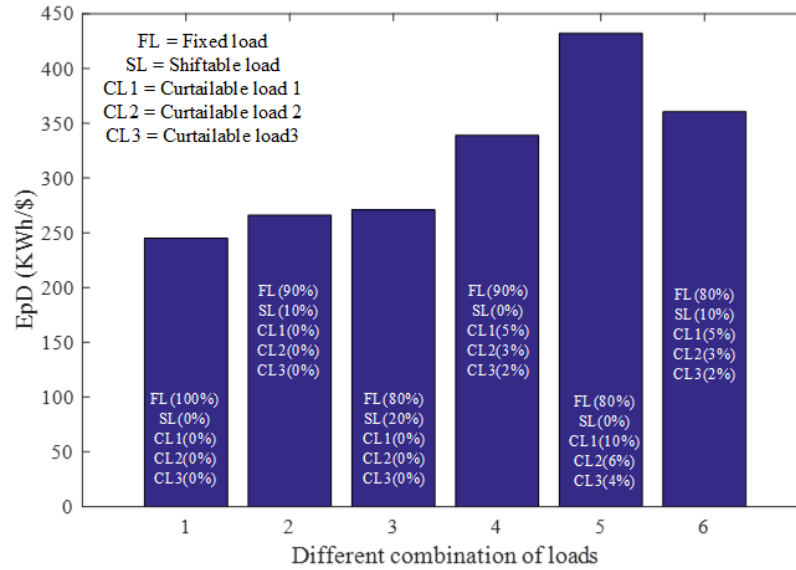


Fig. 18: Impact of DR programs on resilience improvement with the proposed index

Case 4:

In this case, the impact of the initial SOC of the battery and fuel availability in the microgrids on the resilience improvement of distribution network are investigated. Similar to case 3, the microgrid type 2 is considered. Fig. 19

shows the EpD index based on the fuel availability of each generator. As mentioned earlier, the fuel availability in this paper is modeled to be equivalent to the amount of active power that each generator can produce.

According to Fig. 19, with increasing fuel availability for each generator, the microgrid can improve the resilience of distribution network. Thus, fuel availability in the microgrid has an important role in EMS to purchase more and cheaper energy to distribution network.

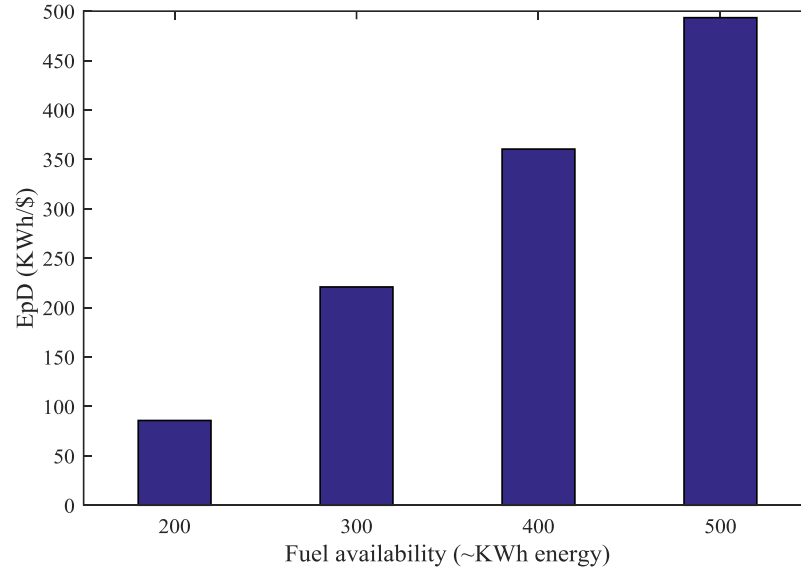


Fig.19: Impact of fuel availability on resilience improvement

The initial SOC of the battery is another important parameter that has important impact on EMS. It is obvious that battery size is also very important for having higher initial available energy in the battery. Fig. 20 confirms the resilience improvement of distribution network by higher initial SOC of battery.

Therefore through well-planning of the needed infrastructures in microgrids (such as fuel tanks and energy storage options), both microgrid and distribution network will be benefited.

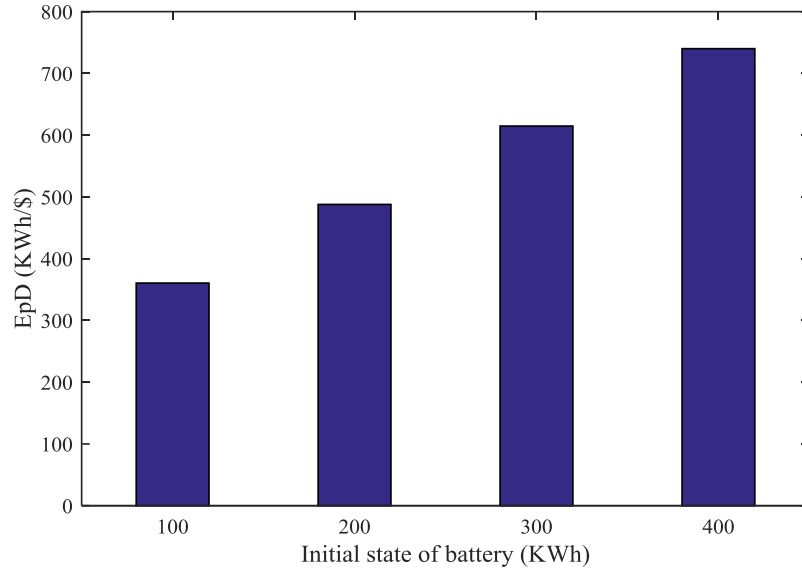


Fig.20: Impact of initial SOC of battery on resilience improvement

5. CONCLUSION

This paper proposed an efficient interaction framework between distribution network and microgrids to enhance resilience against natural disasters such as hurricane and flood when both PDN and WDN can be damaged. The proposed framework includes two main parts: 1) stochastic energy management system for microgrids that considers local load reliability and stochastic parameters, such as loads, renewable power generation and fuel arrival time, and 2) restoration program for distribution networks with the objective of maximizing the accessibility of loads to power and water. The proposed framework was applied to the modified IEEE 33-bus distribution system with connected microgrids and its designed water network. The results confirmed that the proposed energy management system could enable the microgrids as backup energy sources with different capacities, and accordingly help DSO to effectively maximize the accessibility of loads to power and water. Water satisfaction function has important role in water pumps restoration. Hence, this function should be defined carefully. Simulation results also demonstrated that responsive loads could serve as an efficient tool for improving the resilience of distribution network. Moreover, the amount of fuel availability and the battery placed in microgrids could more energy with cheaper incentive price for distribution network.

REFERENCES

- [1] R. Brown, X. Wang, and C. Page, "Are Power Utilities in Tonga and New Zealand Resilient?," 2016.

- [2] E. O. o. t. P. C. o. E. Advisers, *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages*: The Council, 2013.
- [3] Y. Zhang, N. Yang, and U. Lall, "Modeling and simulation of the vulnerability of interdependent power-water infrastructure networks to cascading failures," *Journal of Systems Science and Systems Engineering*, vol. 25, pp. 102-118, 2016.
- [4] V. Krishnamurthy, A. Kwasinski, and L. Duenas-Orsorio, "Comparison of power and telecommunications dependencies and interdependencies in the 2011 tohoku and 2010 maule earthquakes," *Journal of Infrastructure Systems*, vol. 22, p. 04016013, 2016.
- [5] T. N. A. of sciences, *Disaster resilience: A national imperative*. Washington, DC: The National Academies Press, 2012.
- [6] H. T. Tran, M. Balchanos, J. C. Domercant, and D. N. Mavris, "A framework for the quantitative assessment of performance-based system resilience," *Reliability Engineering & System Safety*, vol. 158, pp. 73-84, 2017.
- [7] A. Gholami, F. Aminifar, and M. Shahidehpour, "Front lines against the darkness: Enhancing the resilience of the electricity grid through microgrid facilities," *IEEE Electrification Magazine*, vol. 4, pp. 18-24, 2016.
- [8] Z. Bie, Y. Lin, G. Li, and F. Li, "Battling the extreme: a study on the power system resilience," *Proceedings of the IEEE*, vol. 105, pp. 1253-1266, 2017.
- [9] C. Chen, J. Wang, and D. Ton, "Modernizing distribution system restoration to achieve grid resiliency against extreme weather events: an integrated solution," *Proceedings of the IEEE*, vol. 105, pp. 1267-1288, 2017.
- [10] C. Chen, J. Wang, F. Qiu, and D. Zhao, "Resilient distribution system by microgrids formation after natural disasters," *IEEE Transactions on smart grid*, vol. 7, pp. 958-966, 2016.
- [11] F. Wang, C. Chen, C. Li, Y. Cao, Y. Li, B. Zhou, and X. Dong, "A multi-stage restoration method for medium-voltage distribution system with DGs," *IEEE Transactions on Smart Grid*, vol. 8, pp. 2627-2636, 2017.
- [12] M. Fotuhi-Firuzabad, A. Safdarian, M. Moeini-Aghtaie, R. Ghorani, M. Rastegar, and H. Farzin, "Upcoming challenges of future electric power systems: sustainability and resiliency," *Scientia Iranica*, vol. 23, pp. 1565-1577, 2016.
- [13] L. Che, M. Khodayar, and M. Shahidehpour, "Only connect: Microgrids for distribution system restoration," *IEEE Power and Energy Magazine*, vol. 12, pp. 70-81, 2014.
- [14] J. Li, X.-Y. Ma, C.-C. Liu, and K. P. Schneider, "Distribution system restoration with microgrids using spanning tree search," *IEEE Transactions on Power Systems*, vol. 29, pp. 3021-3029, 2014.
- [15] H. Gao, Y. Chen, Y. Xu, and C.-C. Liu, "Resilience-oriented critical load restoration using microgrids in distribution systems," *IEEE Transactions on Smart Grid*, vol. 7, pp. 2837-2848, 2016.
- [16] Y. Xu, C.-C. Liu, K. P. Schneider, F. K. Tuffner, and D. T. Ton, "Microgrids for service restoration to critical load in a resilient distribution system," *IEEE Transactions on Smart Grid*, vol. 9, pp. 426-437, 2018.
- [17] A. Kwasinski, V. Krishnamurthy, J. Song, and R. Sharma, "Availability evaluation of micro-grids for resistant power supply during natural disasters," *IEEE Transactions on Smart Grid*, vol. 3, pp. 2007-2018, 2012.
- [18] V. Krishnamurthy and A. Kwasinski, "Effects of power electronics, energy storage, power distribution architecture, and lifeline dependencies on microgrid resiliency during extreme events," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, pp. 1310-1323, 2016.
- [19] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Stochastic energy management of microgrids during unscheduled islanding period," *IEEE Transactions on Industrial Informatics*, vol. 13, pp. 1079-1087, 2017.
- [20] A. Hussain, V.-H. Bui, and H.-M. Kim, "Optimal operation of hybrid microgrids for enhancing resiliency considering feasible islanding and survivability," *IET Renewable Power Generation*, vol. 11, pp. 846-857, 2017.
- [21] A. Khodaei, "Resiliency-oriented microgrid optimal scheduling," *IEEE Transactions on Smart Grid*, vol. 5, pp. 1584-1591, 2014.
- [22] J. Dong, G. Xue, and R. Li, "Demand response in China: Regulations, pilot projects and recommendations—A review," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 13-27, 2016.
- [23] A. Anvari-Moghaddam, J. M. Guerrero, J. C. Vasquez, H. Monsef, and A. Rahimi-Kian, "Efficient energy management for a grid-tied residential microgrid," *IET Generation, Transmission & Distribution*, vol. 11, pp. 2752-2761, 2017.
- [24] N. Nikmehr, S. Najafi-Ravadanegh, and A. Khodaei, "Probabilistic optimal scheduling of networked microgrids considering time-based demand response programs under uncertainty," *Applied energy*, vol. 198, pp. 267-279, 2017.
- [25] A. Zakariazadeh, O. Homaei, S. Jadid, and P. Siano, "A new approach for real time voltage control using demand response in an automated distribution system," *Applied Energy*, vol. 117, pp. 157-166, 2014.
- [26] A. Malik and J. Ravishankar, "A hybrid control approach for regulating frequency through demand response," *Applied energy*, vol. 210, pp. 1347-1362, 2018.

- [27] F. Wang, H. Xu, T. Xu, K. Li, M. Shafie-Khah, and J. P. Catalão, "The values of market-based demand response on improving power system reliability under extreme circumstances," *Applied energy*, vol. 193, pp. 220-231, 2017.
- [28] A. Hussain, V.-H. Bui, and H.-M. Kim, "Impact analysis of demand response intensity and energy storage size on operation of networked microgrids," *Energies*, vol. 10, p. 882, 2017.
- [29] J. Najafi, A. Peiravi, A. Anvari-Moghaddam, and J. M. Guerrero, "Resilience improvement planning of power-water distribution systems with multiple microgrids against hurricanes using clean strategies," *Journal of Cleaner Production*, 2019.
- [30] J. Najafi, A. Peiravi, and J. M. Guerrero, "Power distribution system improvement planning under hurricanes based on a new resilience index," *Sustainable Cities and Society*, vol. 39, pp. 592-604, 2018.
- [31] M. Panteli and P. Mancarella, "The grid: Stronger bigger smarter?: Presenting a conceptual framework of power system resilience," *IEEE Power Energy Mag*, vol. 13, pp. 58-66, 2015.
- [32] (30.04.2018). https://www.fema.gov/media-library-data/20130726-1820-25045-9850/hzmmh2_1_hr_tm.pdf.
- [33] S. Ma, B. Chen, and Z. Wang, "Resilience enhancement strategy for distribution systems under extreme weather events," *IEEE Transactions on Smart Grid*, vol. 9, pp. 1442-1451, 2018.
- [34] A. J. Conejo, M. Carrión, and J. M. Morales, *Decision making under uncertainty in electricity markets* vol. 1: Springer, 2010.
- [35] N. Grawe-Kuska, H. Heitsch, and W. Romisch, "Scenario reduction and scenario tree construction for power management problems," in *Power tech conference proceedings, 2003 IEEE Bologna*, 2003, p. 7 pp. Vol. 3.
- [36] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Transactions on Power delivery*, vol. 4, pp. 1401-1407, 1989.