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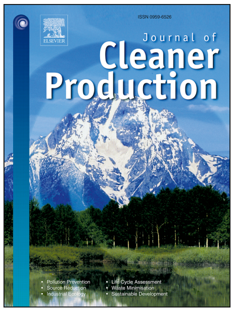

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Resilience Improvement Planning of Power-Water Distribution Systems with Multiple Microgrids against Hurricanes using Clean Strategies

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Abstract: This paper proposes a comprehensive planning framework including a main problem and two sub-problems to enhance the resilience of power distribution network (PDN) and water distribution network (WDN) with multiple microgrids against hurricanes. The main problem which is formulated in stochastic programming aims to minimize the investment cost of resilience improvement strategies and the expected inaccessibility values of loads to power and water under hurricanes. Line hardening in PDN, upgrading the energy storage size in microgrids and water tanks in WDN are considered as three clean candidate strategies. In analyzing each scenario of the main problem, the microgrids which are connected to the PDN are modeled as emergency sources through the first stochastic sub-problem that can restore disconnected loads and water pumps. Water pumps as critical loads are equipped with emergency generators with limited fuel capacity. If there are some water pumps which cannot be restored in each scenario of the main problem, their emergency generators will be scheduled with the second sub-problem of the model. The proposed model is tested on the modified IEEE 33-bus PDN with multiple microgrids and a designed WDN, and the effectiveness of the proposed method is validated accordingly.

Keywords: Microgrids, resilience improvement planning, stochastic linear programming, power network, water network.

1. INTRODUCTION

The U.S. Hurricane Sandy in 2012 caused inaccessibility of approximately 7 million people to electric power (Bie et al., 2017). This hurricane also resulted in many water pumps outages and accordingly loss of clean water in New York City (Zhang et al., 2016). 90 % of faults due to natural disasters occurs in power distribution networks (PDNs) (Advisers, 2013). Therefore, PDN as an vital energy sector must be prepared in the operation and planning phases to face the low-probability but high-impact events (Espinoza et al., 2016). To do so, a number of challenges in terms of the following questions should be addressed: Which resilience improvement strategies should be adopted? How should they be modeled and implemented to satisfy the planer's needs? Finally, which solution methodology can be used to efficiently yield optimal solutions?

In this regard, (Yuan et al., 2016) proposed a two-stage robust programming model to solve the resilience improvement planning of a PDN with lines hardening and fuel-based distributed generators (DGs) placement as candidate strategies. In the same work, due to the limitation of robust programming, only a predetermined number of power lines is assumed to be damaged against hurricanes. Furthermore, it is assumed that if a power line is chosen to be hardened, this line wouldn't be damaged in case of an event occurrence. However, in reality, line hardening denotes a process to decrease the failure probability of a power line against extreme events. Another limitation of the mentioned work is that the studied PDN is a simple network having no tie line for power rerouting. Therefore, reconfiguration of the network as an important operational tool is not available to restore the disconnected loads. (Lin and Bie, 2018) built a tri-level hardening plan to enhance the resilience of a PDN. Although, reconfiguration of the PDN is used in the proposed model to restore the disconnected loads with fuel-based DGs, the mention limitations in the previous work including the number of lines that can be damaged against hurricanes and hardening of a power line have not been solved. Furthermore, in both previous works, the fragility function of a power line is not considered to calculate the failure probability of a power line against hurricane severity denoting that all the power lines have the same probability to be damaged against any hurricane. (Ma et al., 2018) solve the resilience improvement planning problem through a tri-level optimization model and the candidate strategies are reported as line hardening and vegetation management. In the first level, the problem identifies vulnerable distribution lines and select hardening strategies. In the second level, considering the hurricane speed and fragility function of each power line, the set of damaged power lines is determined and the worst-case scenario for PDN damage is realized. Finally, the third level tries to minimize the load shedding cost according to load priorities and the set of damaged lines. Although diesel generators exist in the studied PDN, reconfiguration of the network due to the limitation of the proposed mathematic model is not considered.

DGs have an important role on the resilience improvement of the PDNs, especially when the reconfiguration of the network is also considered. In the previous works, all DGs which are implemented are fuel based DGs. This strategy has two main challenges. First, due to the adverse impact of fossil fuels on the environment, the design of recent energy systems in any conditions such as stand-alone (Giallanza et al., 2018; Mandal et al., 2018), urban (Chen et al., 2018) and even remote communities (Halabi and Mekhilef, 2018) is based on the CO2 emission reduction. The second challenge is to provide enough fuel for DGs during an emergency period which might take a long time. Moreover, storing a large amount of fuel to handle such a situation is difficult, dangerous and expensive.

One of the most effective strategies for enhancing the resilience of distribution systems is to incorporate microgrids. Microgrids are small power networks that could be operated in islanded or grid-connected mode while accommodating different energy sources (e.g., dispatchable generators, renewable energies such as solar and wind) and energy storages (Dragicevic et al., 2017). The lessons learned from natural disasters show microgrids are appropriate option to enhance the resilience. The Sendai microgrid survived for two days in islanded mode during the March 2011 earthquake and tsunami in Japan (Che et al., 2014). (Li et al., 2014) implemented microgrids for load restoration capabilities after faults in distribution systems. In the same work, microgrids are modeled with specified active and reactive power, and spanning tree search is utilized to solve the restoration problem. (Gao et al., 2016) presented another approach for restoring the critical loads of distribution networks by microgrids. In this sense, the concept of Continuous Operating Time (COT) is proposed to determine the maximum time that a microgrid can supply electricity to critical loads. The problem is solved with a two-stage heuristic approach. A strategy table including the different feasible restoration paths is built in the first stage, and the best path is determined thereafter using integer linear programming. (Xu et al., 2018) similar to (Li et al., 2014) implemented microgrids to restore critical loads in distribution systems, while their stability during load restoration is also considered. The lifeline of DGs and local battery affect the availability of microgrids during and after natural disasters (Kwasinski et al., 2012). In addition to the information presented in (Kwasinski et al., 2012). (Krishnamurthy and Kwasinski, 2016) believe more parameters such as microgrid architecture, transportation time of fuel, existing diesel generators, and power electronic interfaces should be considered to quantify microgrid availability during natural disasters. Demand response (DR) as an efficient tool to change the load for a specific goal such as power loss or CO2 minimization is one of the key enabling technologies for microgrids (Shariatzadeh et al., 2015). DR can play an efficient role in the interaction between a microgrid and a PDN.

So far many works such as (Zeng et al., 2014) have studied the problem of providing enough water resources for a city or society in long periods, however, supplying water in shorter periods specially during harsh conditions triggered after a natural disaster is also vital. Similar to PDN, a malfunction in water infrastructure under hurricanes impacts cities and societies. Direct damages of a WDN against hurricanes is much less compared to a PDN. Buried water pipes are not vulnerable against hurricanes. Although, water tanks can be damaged in hurricanes, the number of water tanks in a WDN is much less compared to other components. Therefore, they can be hardened well. Especially, recent water tanks are designed to withstand wind speed of 150 mph. However, the main reason of load inaccessibility to water against hurricanes is the dependency of WDN on PDN which mainly relates to water pumps. Water pumps in WDNs are responsible to circulate water throughout the system. Thus, if the electricity supply of water pumps is disconnected, the operation of WDNs will be interrupted or stopped accordingly. It should be noticed that the dependencies of power and water infrastructures to each other exist at different levels. For example, (Zeng et al., 2017) study the dependency of electricity generation on the capacity of water storage reservoirs in a river. Therefore, the dependency of water network on power networks should be considered in the resilience improvement study. If the resilience improvement of PDN targets only increased accessibility of loads to one commodity (either power or water), the social welfare will be decreased certainly. Unlike numerous works which have studied the resilience improvement of individual PDNs against hurricanes in recent years, a few works have investigated the resilience improvement of a joint PDN and WDN. (Zhang et al., 2016) showed that the dependency of water network on power network increases their vulnerability to cascading failures using graph theory. (Guidotti et al., 2016) studied the resilience of PDN and WDN against earthquake. As a result of this study, the recovery time of WDN can be increased if the dependency of WDN on PDN is considered. In the same study, the PDN is simply modeled without any technical equation related to PDN. (Najafi et al., 2018) showed that the dependency of WDN on PDN could be decreased by DG (with unlimited fuel) placement in PDN, however no restoration mechanism for water pumps was considered. This option should be modeled in resilience studies as in reality, an emergency generator with limited fuel is normally considered in all pumping substation.

This paper proposes a comprehensive planning framework including a main problem and two sub-problems to enhance the resilience of joint PDN and WDN with multiple microgrids against hurricanes. Three clean strategies including line hardening, upgrading the energy storage size in microgrids and water tanks in WDN are considered to enhance the resilience.

Compared to the reviewed literature, the main contributions of the paper are listed below.

1) A comprehensive stochastic model forming a main problem and two sub-problems is proposed to improve the resilience of joint PDN and WDN. The main problem minimizes the expected loads inaccessibility to power and water against hurricanes and investment cost of strategies. In the first sub-problem, microgrids are modeled as energy sources. Water pumps as critical loads are equipped with back-up generators with limited fuel capacity. In the second sub-problem, the back-up generators of the disconnected water pumps are scheduled to maximize the accessibility of loads to water.

2) An interaction framework between microgrids and Distribution System Operator (DSO) who is responsible for restoration of PDN and WDN is proposed to determine the amount of energy that each microgrid can deliver to distribution network considering the reliability of each microgrid local load. In the proposed interaction, fuel arrival time to generators as an uncertain parameter is also considered.
3) Energy storage size upgrading in microgrids is proposed as an efficient solution to enhance the resilience of PDN and WDN. With this strategy, each microgrid can deliver more energy to PDN in emergency conditions.
4) Upgrading the water tanks size in WDN is also considered in resilience improvement planning phase to improve the accessibility of users to water after natural disasters.

The rest of this paper is organized as follow. Sections 2 discusses the model description including the framework of the problem, formulation and solution of the proposed resilience improvement planning model for power-water distribution systems. Numerical case studies are presented in Section 3, and Section 4 concludes the paper.

2. MODEL DESCRIPTION

In this section, different parts of the proposed model including a general framework of the problem, mathematical formulation and solution methodology will be explained.

2.1. Comprehensive resilience improvement planning framework

Fig. 1 shows a typical PDN and its related designed WDN. In such an integrated energy system, it is assumed that several microgrids are connected to the PDN. Each microgrid has its local generation sources and loads that can be operated isolated or connected to the PDN. Two water pumps are located in the WDN which are fed by the corresponding nodes in the PDN. As well as, each water pump is equipped with a fuel-based DG (emergency generator) with limited fuel capacity. 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.

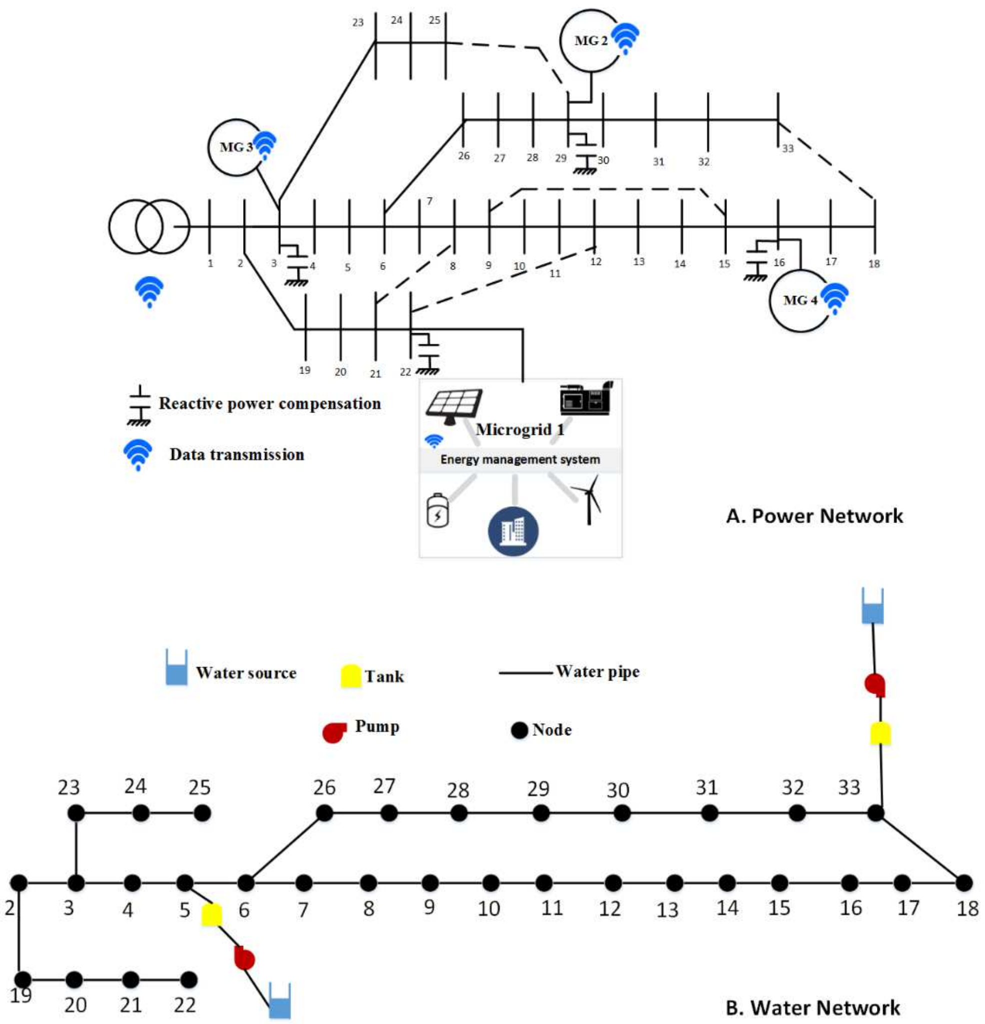


Fig. 1: Power distribution network with connected microgrids and related designed water network

There are many uncertain parameters in this problem which are listed in Fig. 2.

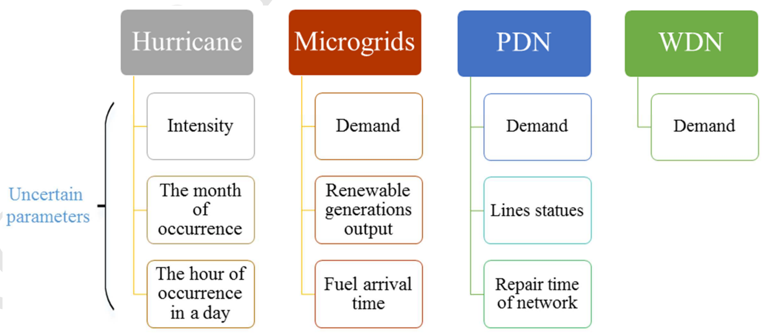


Fig. 2: Uncertain parameters in the proposed model

The uncertainty of each parameter will be modeled with a probability distribution function presented in Section 4. In the proposed model, all the uncertain parameters will be addressed through two Stochastic Optimization Programming (SOP) problems. The first SOP is the resilience improvement planning of PDN and WDN as the main problem of the proposed comprehensive planning framework. In this SOP, a set of scenarios with regards to the uncertain parameters of the hurricane, PDN and WDN are produced. During each operating scenario, the interaction of microgrids and PDN will be investigated through the second SOP where the stochastic Energy Management System (EMS) for each microgrid as the first sub-problem of the proposed model determines the value of energy that can be delivered to the PDN. It is clear that scenarios in the second SOP will capture the uncertain parameters of each microgrid. Backward scenario reduction as a well-known method is implemented in this paper to reduce the number of the generated scenarios in both SOPs. This method is comprehensively explained in (Growe-Kuska et al., 2003).

In case of a hurricane in a scenario of first SOP, a major part of the PDN could be damaged resulting to many distribution lines outages. To tackle such an emergency condition, DSO could reconfigure the network with the aid of tie lines switches and microgrids (which are also assumed to be owned by the DSO). Each microgrid will run the designed stochastic EMS (first sub-problem) with the objective of maximizing the delivered energy to the PDN considering the reliability of local loads. One of the most important pieces of data which is needed by the EMS to meet the objectives 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 the emergency period.. 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 delivered by the microgrids in different hours of the emergency period must be proportional to the number of restored loads. However, as the aggregated load profile often varies with a specific coefficient at different hours, this data is also needed for EMS. With this information, each microgrid runs the EMS and determine the amount of energy to be delivered to the PDN in each interval of the emergency period.

If the power supply of the water pumps is unavailable due to hurricanes, the operation of WDN will be interrupted or stopped accordingly. However, to understand the water pressure at different nodes of the system in different operation states of water pumps and water level in each tank, it is essential to analyze the water network. In this regard, a water distribution system modeling software package (EPANET) is utilized to accurately track the flow of water in each pipe, the pressure at each node, and the height of the water in each tank through the entire WDN. It is further assumed that the inaccessibility of loads to water is mainly caused by electric power outage during the emergency period. During each scenario of the first SOP, if the disconnected water pumps cannot be restored, their emergency generators will be scheduled through the second sub-problem of the model with the objective of maximizing the accessibility of loads to water.

To formulate the problem in a tractable manner, several assumptions are made as follows: First, the fragility of power poles and conductors in PDN are assumed to be higher than other components against hurricanes.

Therefore, hardening is primarily considered for these assets. The basis for this assumption can be listed as follow: 1) The main important components in PDN are power poles and conductors which are responsible to deliver energy from energy sources to customers, 2) Similar components have also been considered in previous works (such as (Ma et al., 2018)) to be vulnerable in PDN against hurricane, and 3) The number of these components in PDN is much higher than other components. Microgrids are also assumed resilient enough against hurricanes (as discussed in the introduction). Finally, as there is no benchmark system for joint PDN and WDN studies, it is assumed that a water network is carefully designed for the existing IEEE 33-bus distribution system. To this end, according to Fig. 1, it is assumed that each node (except nodes 5 and 33) in PDN as a residential or commercial load has a corresponding node in WDN. It is further assumed that power loads in nodes 5 and 33 are water pumps. So, the water consumption of these loads is zero. The characteristic of pipes and amount of water consumption for each node in WDN are determined according to the amount of power consumption of each load in PDN.

2.2. Problem formulation

In this section, the proposed model including the main problem and two sub-problems is formulated. The main problem of the model is a stochastic programming with two objective functions. The first objective function (OF_1) minimizes the expected inaccessibility values of loads to power and water under hurricanes.

$$OF_1 = \min \sum_{s=1}^{N_s} \rho_s \sum_{l=1}^{N_l} \sum_{t=t_s^0}^{t_s^0+T_s} \left(IVP_{l,t}(1-\alpha_{s,l,t}) + IVW_{l,t}(1-\beta_{s,l,t}) \right) \tag{1}$$

where s, N_s and ρ_s are index, number of scenarios and probability of each scenario in the main problem of the model, respectively. l and N_l are index and number of loads in both PDN and WDN, respectively. t, t_s^0 and T_s are time index, the initial time of the emergency period in scenario *s* and emergency period in scenario *s* due to hurricane, respectively. $IVP_{l,t}$ and $IVW_{l,t}$ are inaccessibility value of load *l* to power and water at time *t*, respectively.

In equation (1), α is a binary variable that indicates the state of loads in the PDN.

$$\alpha = \begin{cases} 1 & \text{if load is connected} \\ 0 & \text{if load is disconected} \end{cases} \tag{2}$$

β is the accessibility function of loads to water which is shown in Fig. 3. In other words, β indicates the satisfaction level of consumers' access to water after a natural disaster such as a hurricane. Water accessibility of a load is proportional to water pressure in the node including the load. A minimum water pressure is required to obtain the full satisfaction level.

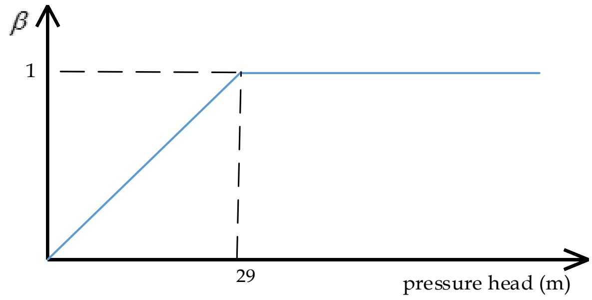


Fig. 3: Satisfaction function of the loads to water

The second objective function of the problem (OF_2) minimizes the budget or in other words investment cost of resilience improvement strategies.

$$OF_2 = \min \sum_{k=1}^{N_k^p} \Omega_k C_k^H + \sum_{m=1}^{mg} \sum_{bs=1}^{N_{bat}^{stra}} \Psi_{m,bs} C_{m,bs}^{Batt} + \sum_{d=1}^{N_{Tank}^{water}} \sum_{ts=1}^{N_{ts}^{stra}} \lambda_{d,ts} C_{d,ts}^{Tank} \tag{3}$$

where k and N_k^p are index and number of power lines in PDN, respectively. m and mg are index and number of microgrids, respectively. bs and N_{bat}^{stra} are index and number of strategies for battery size, respectively. d and N_{Tank}^{water} are index and number of water tanks in WDN, respectively. ts and N_{tnk}^{stra} are index and number of different strategies for water tank size, respectively. $\Omega_k, \Psi_{m,bs}$ and $\lambda_{d,st}$ are binary variables determining line k is hardened or not, battery size in microgrid m is upgraded to strategy bs or not and size of water tank d is upgraded to strategy ts or not, respectively.

The size of each battery or each water tank can be upgraded only with one of the related strategies which is indicated in (4).

$$\begin{cases} \sum_{bat=1}^{N_{bat}^{stra}} \Psi_{m,bat} \in \{0,1\} & m \in \{1,2,...,mg\} \\ \sum_{\tan}^{N_{\tan}^{stra}} \lambda_{d,\tan} \in \{0,1\} & d \in \{1,2,...,N_{Tank}^{water}\} \end{cases} \tag{4}$$

For each scenario, the DSO should solve the restoration problem. The DSO has two options to restore the loads. The first option is the reconfiguration of the main network which is supplied by the substation and the second one is the system partitioning through intentional islanding of a microgrid or microgrids. To apply the latter, DSO should know the amount of energy that each microgrid can deliver to the PDN during an emergency period. Therefore, each microgrid has to solve the designed stochastic EMS as the first sub-problem of the model described in (5)-(22).

The decision variables in the EMS of each microgrid are categorized into the following two groups. The first group consists of *here-and-now* variables which are made before the realization of the stochastic process. The second group consists of *wait-and-see* decisions, which are made after knowing the realization of the stochastic process (Conejo et al., 2010). In this paper, the amount of active power delivered to the PDN is considered as a *here-and-now* decision variable while others, such as dispatchable generators power output, and amount of load shedding are *wait-and-see* variables. According to (5), the objective of EMS for each microgrid is to maximize the delivered energy to PDN considering the expected energy not served locally. The first term of (5) is a deterministic function and the second term is the recourse function.

$$\left[\max \left(\sum_{t=t_s^0}^{T^s} pdeliv_{t,m}^s - \sum_{s'=1}^{N_{s'}} \sum_{t=t_s^0}^{T_s} \rho_{s',m}^s pshed_{t,s',m}^s \right) \quad m \in \{1, 2, ..., mg\} \right] \quad s \in \{1, 2, ..., N_s\} \tag{5}$$

where s' and $N_{s'}$ are index and number of scenarios in the EMS for microgrids (first sub-problem). $\rho_{s',m}^s$ is the probability of scenario s' of the first sub-problem in microgrid *m* in scenario *s* of the main problem. $pdeliv_{t,m}^s$ is amount of active power delivered by microgrid *m* at time *t* to distribution system in scenario *s* of the main problem. $pshed_{t,s',m}^s$ is amount of load shedding at time *t* in scenario s' of the first sub-problem in microgrid *m* in scenario *s* of the main problem. With this objective function, the reliability of each microgrid local loads is also considered.

There are three categories of loads in a microgrid: 1) shiftable (*pshift*), 2) curtailable (*pcl*) and 3) fixed (Anvari-Moghaddam et al., 2017). The constraints that must be satisfied in the stochastic EMS for each microgrid are expressed as follows. If the generation is lower than the demand at some hours, and if the microgrid operator cannot address this issue with shiftable and curtailable load, then some loads will be disconnected (*pshed*) to avoid system instability.

DR program is an efficient tool that can be implemented by each microgrid to increase the amount of active power delivered to PDN. Equation (6) is related to the DR program, which determines the amount of load shifted from time interval *t* to time interval *t′* in each scenario.

$$\left[pshf_{t,s',m}^s = \sum_{t'=t_s^0}^{t_s^0+T_s} pshift_{t',t,s',m}^s - pshift_{t,t',s',m}^s \quad t \in [t_s^0, t_s^0+T_s], s' \in \{1,2,...,N_{s'}\}, m \in \{1,2,...,mg\} \right] s \in \{1,2,...,N_s\} \tag{6}$$

where $pshift_{t,t',s',m}^s$ is amount of load which is shifted from time *t* to time t' in scenario s' of the first sub-problem in microgrid *m* in scenario *s* of the main problem. $pshf_{t,s',m}^s$ is total load which is shifted to or from time *t* in scenario s' of the first sub-problem in microgrid *m* in scenario *s* of the main problem.

For each scenario of the first sub-problem, the supply-load power balance is formulated as follows:

$$\begin{bmatrix} load_{t,s',m}^s - \sum_{c=1}^{C_m} pcl_{c,t,s',m}^s + pshf_{t,s',m}^s - pshed_{t,s',m}^s = \sum_{g=1}^{G_m} p_{g,t,s',m}^s - pdeliv_{t,m}^s + pdcr_{t,s',m}^s \\ -pchr_{t,s',m}^s + prdg_{t,s',m}^s \qquad t \in [t_s^0, t_s^0 + T_s], s' \in \{1, 2, ..., N_{s'}\}, m \in \{1, 2, ..., mg\} \end{bmatrix}, s \in \{1, 2, ..., N_s\} \tag{7}$$

where $load^{s}_{t,s',m}$, $pshed^{s}_{t,s',m}$, $prdg^{s}_{t,s',m}$, $pdcr^{s}_{t,s',m}$ and $pchr^{s}_{t,s',m}$ are active power demand, amount of load shedding, power output of renewables generations (wind and solar), charging and discharging power of battery at time t in scenario s' of the first sub-problem in microgrid m in scenario s of the main problem, respectively. c and C_m are index and number of curtailable loads in microgrid m, respectively. $pcl^{s}_{c,t,s',m}$ is amount of load c curtailment at time t in scenario s' of the first sub-problem in microgrid m in scenario s of the main problem. g and G_m are index and number of generators in microgrid m, respectively. $p^{s}_{g,t,s',m}$ is active power of generator g at time t in scenario s' of the first sub-problem in microgrid m in scenario s of the main problem.

In connection to the operation of dispatchable generators, certain constraints must also be met. First, active power of each generator should be scheduled in an allowable range.

$$\begin{bmatrix} p^{\min}_{g,m}u^{s}_{g,t,s',m} \le p^{s}_{g,t,s',m} \le p^{\max}_{g,m}u^{s}_{g,t,s',m} \quad g\in\{1,2,...,G_m\}, t\in[t^0_s, t^0_s+T_s], \\ s'\in\{1,2,...,N_{s'}\}, m\in\{1,2,...,mg\} \end{bmatrix} \quad s\in\{1,2,...,N_s\} \tag{8}$$

where $p^{\min}_{g,m}$ and $p^{\max}_{g,m}$ are minimum and maximum active power of generator g in microgrid m, respectively. $u^{s}_{g,t,s',m}$ is commitment status identifier of generator g at time t in scenario s' of the first sub-problem in microgrid m in scenario s of the main problem.

Ramping down/up limits of each generator are indicated by the following expressions:

$$\begin{bmatrix} p^{s}_{g,t,s',m} - p^{s}_{g,t-1,s',m} \le R^{DN}_{g,m} \quad g\in\{1,2,...,G_m\}, t\in[t^0_s, t^0_s+T_s], \\ s'\in\{1,2,...,N_{s'}\}, m\in\{1,2,...,mg\} \end{bmatrix} s\in\{1,2,...,N_s\} \tag{9}$$

$$\begin{bmatrix} p^{s}_{g,t-1,s',m} - p^{s}_{g,t,s',m} \le R^{UP}_{g,m} \quad g\in\{1,2,...,G_m\}, t\in[t^0_s, t^0_s+T_s], \\ s'\in\{1,2,...,N_{s'}\}, m\in\{1,2,...,mg\} \end{bmatrix} s\in\{1,2,...,N_s\} \tag{10}$$

where $R^{DN}_{g,m}$ and $R^{UP}_{g,m}$ are ramp down and up rate of generator g in microgrid m, respectively.

Start-up and shut-down constraints of each generator are expressed as follows:

$$\begin{bmatrix} y^{s}_{g,t,s',m} - z^{s}_{g,t,s',m} = u^{s}_{g,t,s',m} - u^{s}_{g,t-1,s',m} \quad g\in\{1,2,...,G_m\}, t\in[t^0_s, t^0_s+T_s], \\ s'\in\{1,2,...,N_{s'}\}, m\in\{1,2,...,mg\} \end{bmatrix} \quad s\in\{1,2,...,N_s\} \tag{11}$$

$$\begin{bmatrix} y^{s}_{g,t,s',m} + z^{s}_{g,t,s',m} - 1 \le 0 \quad g\in\{1,2,...,G_m\}, t\in[t^0_s, t^0_s+T_s], \\ s'\in\{1,2,...,N_{s'}\}, m\in\{1,2,...,mg\} \end{bmatrix} s\in\{1,2,...,N_s\} \tag{12}$$

where $y^{s}_{g,t,s',m}$ and $z^{s}_{g,t,s',m}$ are start-up and shut-down identifiers of generator g at time t in scenario s' of the first sub-problem in microgrid m in scenario s of the main problem, respectively.

The capacity of the feeder which connects microgrid m to the PDN is expressed as:

$$\left[pdeliv_{t,m,s} \le Cap^{\max}_{m} \quad t\in[t^0_s, t^0_s+T_s], m\in\{1,2,...,mg\} \right] \quad s\in\{1,2,...,N_s\} \tag{13}$$

where $Cap^{\max}_{m}$ is the maximum energy import/export of microgrid m.

The following expressions are related to the battery operation. The following constraint enforces the state of charge (SOC) to be within the allowable limits:

$$\left[SOC_m^{\min} \le SOC_{t,s',m}^{s} \le SOC_m^{\max} \quad t \in [t_s^0, t_s^0 + T_s], s' \in \{1,2,...,N_{s'}\}, m \in \{1,2,...,mg\}\right] \quad s \in \{1,2,...,N_s\} \tag{14}$$

where $SOC_m^{\min}$ and $SOC_m^{\max}$ are minimum and maximum active power of battery in microgrid *m*, respectively. $SOC_{t,s',m}^{s}$ is state of charge of battery at time *t* in scenario s' of the first sub-problem in microgrid *m* in scenario *s* of the main problem, respectively.

The next constraint indicates the relationship between charging/discharging rates and the SOC:

$$\begin{bmatrix} SOC_{t,s',m}^{s} = SOC_{t-1,s',m}^{s} + pchr_{t,s',m}^{s}\eta_m - \dfrac{pdcr_{t,s',m}^{s}}{\eta_m} \quad t \in [t_s^0, t_s^0 + T_s], s' \in \{1,2,...,N_{s'}\}, \\ m \in \{1,2,...,mg\} \end{bmatrix} \quad s \in \{1,2,...,N_s\} \tag{15}$$

where η_m is efficiency of battery charging or discharging in microgrid *m*.

Charging/discharging rates are defined as follows:

$$\begin{bmatrix} 0 \le pchr_{t,s',m}^{s} \le \dfrac{(SOC_m^{\max} - SOC_{t-1,s',m}^{s})}{\eta_m} \quad t \in [t_s^0, t_s^0 + T_s], s' \in \{1,2,...,N_{s'}\}, \\ m \in \{1,2,...,mg\} \end{bmatrix} \quad s \in \{1,2,...,N_s\} \tag{16}$$

$$\begin{bmatrix} 0 \le pdcr_{t,s',m}^{s} \le (SOC_{t-1,s',m}^{s} - SOC_m^{\min})\eta_m \quad t \in [t_s^0, t_s^0 + T_s], s' \in \{1,2,...,N_{s'}\}, \\ m \in \{1,2,...,mg\} \end{bmatrix} s \in \{1,2,...,N_s\} \tag{17}$$

Some loads in each microgrid are allowed to be curtailed at certain hours as follows:

$$\begin{bmatrix} pcl_{c,t,s',m}^{s} \le lc_{c,t,s',m}^{s} load_{c,m}^{cur,\max} \quad c \in \{1,2,...,C_m\}, t \in [t_s^0, t_s^0 + T_s], \\ s' \in \{1,2,...,N_{s'}\}, m \in \{1,2,...,mg\} \end{bmatrix} \quad s \in \{1,2,...,N_s\} \tag{18}$$

$$\begin{bmatrix} \sum_{t=t_s^0}^{T_s+t_s^0} lc_{c,t,s',m}^{s} \le Tload_{c,m}^{cur,\max} \quad c \in \{1,2,...,C_m\}, t \in [t_s^0, t_s^0 + T_s], \\ s' \in \{1,2,...,N_{s'}\}, m \in \{1,2,...,mg\} \end{bmatrix} s \in \{1,2,...,N_s\} \tag{19}$$

where $load_{c,m}^{cur,\max}$ and $Tload_{c,m}^{cur,\max}$ are maximum active power and maximum duration of curtailable load *c* in microgrid *m*, respectively. $lc_{c,t,s',m}^{s}$ is load *c* status identifier at time *t* in scenario s' of the first sub-problem in microgrid *m* in scenario *s* of the main problem, respectively.

The maximum amount of load that can be shifted from time interval *t* to other time intervals is expressed as:

$$\left[\sum_{t'=t_s^0}^{T_s+t_s^0} pshift_{t,t',s',m} \le load_m^{shift,\max} \quad t \in [t_s^0, t_s^0 + T_s], s' \in \{1,2,...,N_{s'}\}, m \in \{1,2,...,mg\}\right] \quad s \in \{1,2,...,N_s\} \tag{20}$$

The amount of available fuel capacity in each microgrid is limited as:

$$\begin{bmatrix} \sum_{t=t_s^0}^{t_s^0+FAT_{s',m}^{s}} p_{g,t,s',m}^{s} \le Fuel_m^{avial} \quad g \in \{1,2,...,G_m\}, t \in [t_s^0, t_s^0 + T_s], \\ s' \in \{1,2,...,N_{s'}\}, m \in \{1,2,...,mg\} \end{bmatrix} s \in \{1,2,...,N_s\} \tag{21}$$

where $FAT^{s}_{s',m}$ is fuel arrival time to microgrid *m* in scenario s' of the first sub-problem in scenario *s* of the main problem. According to (21), fuel consumption in a microgrid is simply modeled to be proportional to the active power of generators. However, it should be noted that a generator has different fuel consumption rates in its operating range. As mentioned earlier, the power that the microgrid should provide to the PDN must be proportional to the load variation in the PDN. Therefore, the following constraint adjusts the power sold according to load variations in the PDN:

$$\left[pdeliv_{t,m,s} = lf_{t,s}\, pdeliv_{t_h,m,s} \quad t \in [t_s^0, t_s^0 + T_s], m \in \{1,2,...,mg\} \right] \quad s \in \left\{1,2,...,N_s\right\} \tag{22}$$

where $lf_{t,s}$ is the load variation profile in the emergency period in scenario *s* which is normalized based on the lowest demand load at time t_h in the examined period and is reported by DSO to the microgrid.

Having known the amount of energy that each microgrid can deliver during emergency period, the DSO solves the restoration problem for each scenario.

In each time interval within each scenario of the main problem and for each network (main or islanded), the following load flow equations and constraints must also be satisfied. As mentioned before, the main power network is supplied by substation and each islanded network will be supplied by one or more microgrids. Power balance equations in (23)-(24) show that the power injection at bus *i* should be equal to the load demand at bus *i*.

$$P_{i,t,s}^{w} = \left|V_{i,t,s}^{w}\right| \sum_{j} \left|V_{j,t,s}^{w}\right| (G_{ij} \cos\theta_{ij,t,s}^{w} + B_{ij} \sin\theta_{ij,t,s}^{w}) \quad i \in \{1,2,...,N_b^{w,s}\}, t \in [t_s^0, t_s^0 + T_s], \; s \in \{1,2,...,N_s\}, w \in \{1,2,...,W^s + 1\} \tag{23}$$

$$Q_{i,t,s}^{w} = \left|V_{i,t,s}^{w}\right| \sum_{j} \left|V_{j,t,s}^{w}\right| (G_{ij} \sin\theta_{ij,t,s}^{w} - B_{ij} \cos\theta_{ij,t,s}^{w}) \quad i \in \{1,2,...,N_b^{w,s}\}, t \in [t_s^0, t_s^0 + T_s], \; s \in \{1,2,...,N_s\}, w \in \{1,2,...,W^s + 1\} \tag{24}$$

where *w* is an index for power network (islanded or main). W^s is the number of islanded network in scenario *s* of the main problem. *i* and *j* are bus indices. $N_b^{w,s}$ is the number of buses in network *w* in scenario *s* of the main problem. G_{ij} and B_{ij} are conductance and susceptance of the line which connects bus *i* and *j*, respectively. $\theta_{ij,t,s}^{w}$ and $\left|V_{i,t,s}^{w}\right|$ are difference phase voltage angle between bus *i* and *j* and voltage magnitude at bus *i* in network *w* at hour *t* in scenario *s* of the main problem, respectively. $P_{i,t,s}^{w}$ and $Q_{i,t,s}^{w}$ are active and reactive power of the load at bus *i* at hour *t* in network *w* in scenario *s* of the main problem.

Bus voltage line current and should be limited as shown in (25) and (26).

$$\left|V_{\min}\right| \le \left|V_{i,t,s}^{w}\right| \le \left|V_{\max}\right| \quad i \in \{1,2,...,N_b^{w,s}\}, t \in [t_s^0, t_s^0 + T_s], s \in \{1,2,...,N_s\}, w \in \{1,2,...,W^s + 1\} \tag{25}$$

$$\left|I_{ij,t,s}^{w}\right| \le \left|I_{ij}^{\max}\right| \quad i \in \{1,2,...,N_b^{w,s}\}, t \in [t_s^0, t_s^0 + T_s], s \in \{1,2,...,N_s\}, w \in \{1,2,...,W^s + 1\} \tag{26}$$

where $|V_{\min}|$ and $|V_{\max}|$ are minimum and maximum allowable voltage magnitude in the PDN. $|I_{ij,t,s}^{w}|$ and $|I_{ij}^{\max}|$ are the line flow between bus *i* and *j* in network *w* at hour *t* in scenario *s* of the main problem and the maximum allowable line current capacity between bus *i* and *j*, respectively.

According to (27), the structure of the main network or each islanded microgrid should be radial.

$$N_{b}^{w,s} = N_{line}^{w,s} + 1 \quad w \in \{1,2,...,W^{s}+1\} \tag{27}$$

where $N_{line}^{w,s}$ is the number of power lines in network *w* in scenario *s*.

Furthermore, for each islanded network, the following constraints must be satisfied. According to (28), the total demanded active power of the loads plus the active power losses of distribution lines within each network should not exceed the exchanged power between the microgrid(s) and the DSO. The same should be satisfied with reactive power as shown in (29).

$$\sum_{i=1}^{N_{b}^{w,s}} P_{i,t,s}^{w} + Ploss_{t,s}^{w} \leq \sum_{m=1}^{N_{mg}^{w,s}} pdeliv_{t,m,s} \quad t \in [t_{s}^{0}, t_{s}^{0}+T_{s}], s \in \{1,2,...,N_{s}\}, w \in \{1,2,...,W^{s}\} \tag{28}$$

$$\sum_{i=1}^{N_{b}^{w,s}} Q_{i,t,s}^{w} + Qloss_{t,s}^{w} \leq \sum_{i=1}^{N_{b}^{w,s}} Q_{i}^{source} \quad t \in [t_{s}^{0}, t_{s}^{0}+T_{s}], s \in \{1,2,...,N_{s}\}, w \in \{1,2,...,W^{s}\} \tag{29}$$

Where $N_{mg}^{w,s}$ is the number of microgrids in network *w* in scenario *s* of the main problem. Q_{i}^{source} is reactive power of the source which is installed at bus *i*. $Ploss_{t,s}^{w}$ and $Qloss_{t,s}^{w}$ are active and reactive power losses of distribution network lines in network *w* at hour *t* in scenario *s* of the main problem.

To calculate the accessibility of loads to water, it is necessary to formulate the hydraulic model of the WDN. There are three fundamental equations in WDN (Zhang et al., 2017). The first equation is mass conservation that must be satisfied at the nodes except fixed-head nodes such as reservoirs of WDN:

$$\sum_{wp \in LK_{n}} f_{wp,t,s} + F_{n,t,s} = 0 \quad t \in [t_{s}^{0}, t_{s}^{0}+T_{s}], n \in \left\{1,2,...,N_{n}^{water} - NR^{water}\right\}, s \in \{1,2,...,N_{s}\} \tag{30}$$

where *n* and *wp* are node and water pipe indices, respectively. N_{n}^{water} and NR^{water} are number of all nodes and fixed-head nodes in WDN. LK_{n} is the set of all links (pipes) connected to node *n* in WDN. $F_{n,t,s}$ is node *n* demand at time *t* in scenario *s* of the main problem. $f_{wp,t,s}$ is pipe *wp* flow rate at hour *t* in scenario *s* of the main problem.

Moreover, energy conservation must be satisfied in each simple loop of water network.

$$\sum_{wp=1}^{wp_{ls}} h_{wp,ls,t,s} = 0 \quad ls \in \left\{1,2,...,LS\right\}, t \in [t_{s}^{0}, t_{s}^{0}+T_{s}], s \in \{1,2,...,N_{s}\} \tag{31}$$

where *ls* and *LS* are index and number of simple loops in WDN, respectively. $h_{wp,ls,t,s}$ is hydraulic head loss of pipe w*p* in loop *ls* at hour *t* in scenario *s* of the main problem.

The last equation represents the hydraulic head loss. This equation indicates the head loss of a pipe as a function of the flow through the pipe.

$$h_p = x f_p^{\ y} \tag{32}$$

x and *y* are coefficients which determined based on the Hazen-Williams model.

As mentioned before, if the DSO cannot restore all disconnected water pumps, the back-up generators of the disconnected water pumps will be dispatched. Due to fuel limitation of these generators and possibility of having a long period of emergency, these generators should be operated in a way that the inaccessibility of loads to water be minimized. This objective function is indicated in (33).

$$\min \sum_{l=1}^{N_l} \sum_{t=t_s^0}^{t_s^0+T_s} IVW_{l,t}(1-\beta_{s,l,t}) \quad \forall s \in \{1,2,...,N_s\} \tag{33}$$

According to (34), each generator can supply such a load for a limited duration.

$$\sum_{t=t_s^0}^{t_s^0+T_s} \Phi_{t,wp,s} \le T_{wp}^{\max} \quad \forall wp \in \{1,2,...,WP\}, \forall s \in \{1,2,...,N_s\} \tag{34}$$

where $\Phi_{t,wp,s}$ is a binary variable for determining the state of backup generator which supplies water pump *wp* at time *t* in scenario *s* of the main problem. $T_{wp}^{\max}$ is maximum time that backup generator can supply water pump *wp*. Other constraints related to the hydraulic system operation in WND should also be met (equations in (30)-(32)).

2.4. Solution Methodology

Fig. 4 shows the procedure for solving the proposed resilience improvement planning problem. Greedy search as an iterative algorithm is utilized in this paper to solve the problem. In order to implement the greedy search algorithm, the aforementioned objective functions are mapped into the following mixed-objective function:

$$OF = \max \frac{OF_1^{itr-1} - OF_1^{itr}}{\mathrm{cost}_{RIST}} \quad RIST \in \{1,2,...,N_{RIST}\} \tag{35}$$

where *RIST* and N_{RIST} are index and number of candidate resilience improvement strategies. cost_{RIST} is cost of strategy *RIST*. According to (35), in each iteration of the greedy search algorithm, the problem is solved considering the objective function (35) which is indicating the difference of resilience improvement (expected inaccessibility of loads to power and water) compared to the previous iteration (*itr-1*) per cost of each chosen strategy. This iterative procedure will be continued until the maximum budget (determined by the planner) is exhausted.

As can be seen from Fig. 4, the proposed model includes a main problem and two sub-problem that should be solved. The first sub-problem captures the interaction of the microgrids with the PDN through dedicated EMSs for the microgrids in forms of (5)-(22). The aim of this part is to determine the amount of delivered energy to PDN by each microgrid in emergency period. According to (5)-(22), this sub-problem is linear and can be solved by any related solution algorithms/ solvers such as CPLEX. The main problem captures the restoration phase. To handle this, the results of the first sub-problem (EMS) together with a detailed analysis of the water network is needed. The latter is performed in EPANET considering equations (30)-(32). The restoration problem is solved based on the graph theory and a modified Viterbi algorithm detailed in (Najafi et al., 2018). The second sub-problem will be taken into consideration in each scenario if all the disconnected water pumps cannot be restored. The aim of this part is to schedule the back-up generators to feed the disconnected water pumps during emergency period. This sub-problem with the objective function outlined in (33) and constraints (30)-(32), (34) is solved with a genetic algorithm designed in MATLAB while having EPANET in the loop to analyze the WDN operation.

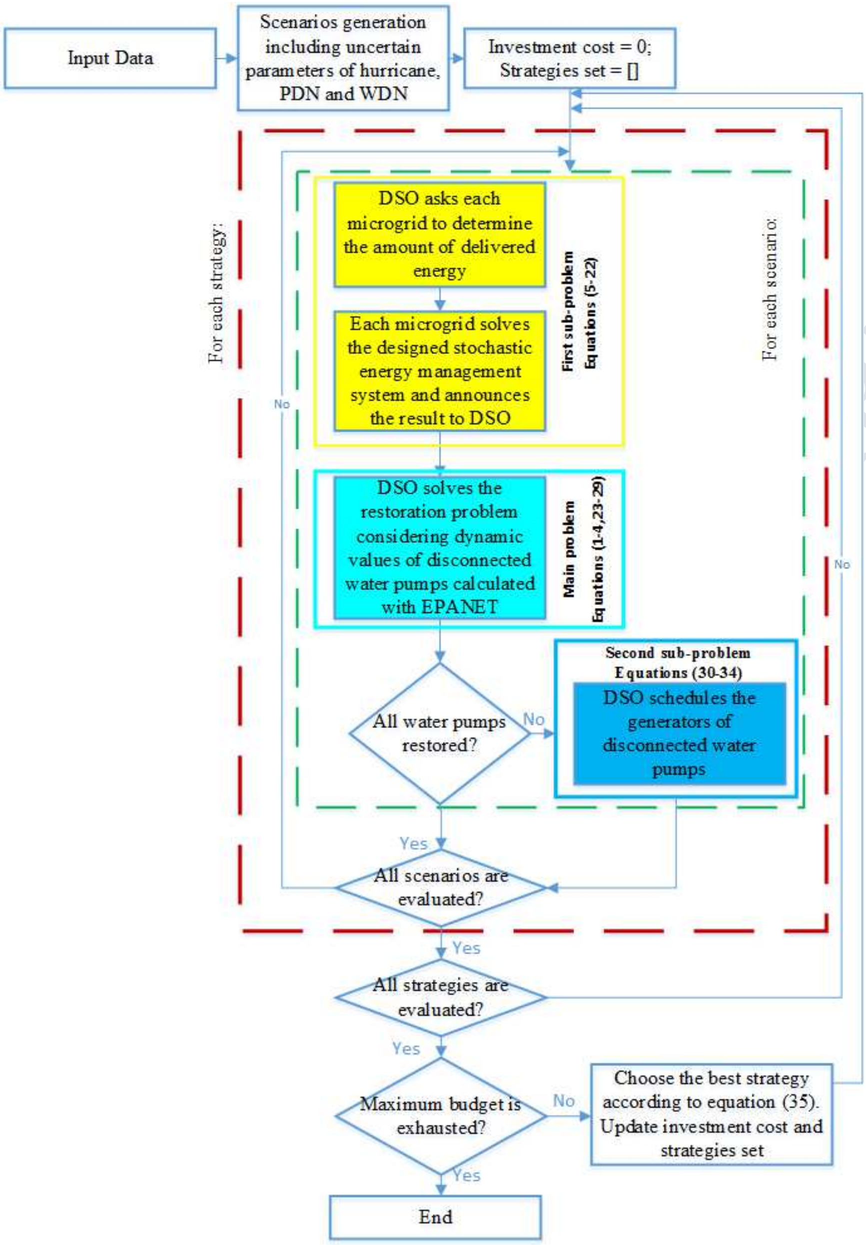


Fig. 4: Flowchart of solving the problem

3. RESULTS

To illustrate the effectiveness of the proposed method, the modified IEEE 33 bus PDN with connected microgrids and its related designed WDN as shown in Fig. 1 is studied.

Microgrids Data:

It is assumed that the two microgrids in nodes 16 and 22 are similar and they are labeled as microgrids type 1. The microgrids in nodes 3 and 29 are also similar and named as microgrids type 2. The difference between these two types lies mainly on their generation mix and demand level. The parameters of dispatchable generators in microgrids which are obtained from (Hussain et al., 2017) are shown in Table 1.

Table 1: Dispatchable generators parameters in microgrid

No.	p_g^{min} (kW)	p_g^{max} (kW)	A_g ($)	B_g ($/kWh)	SUC_g ($)	SDC_g ($)
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

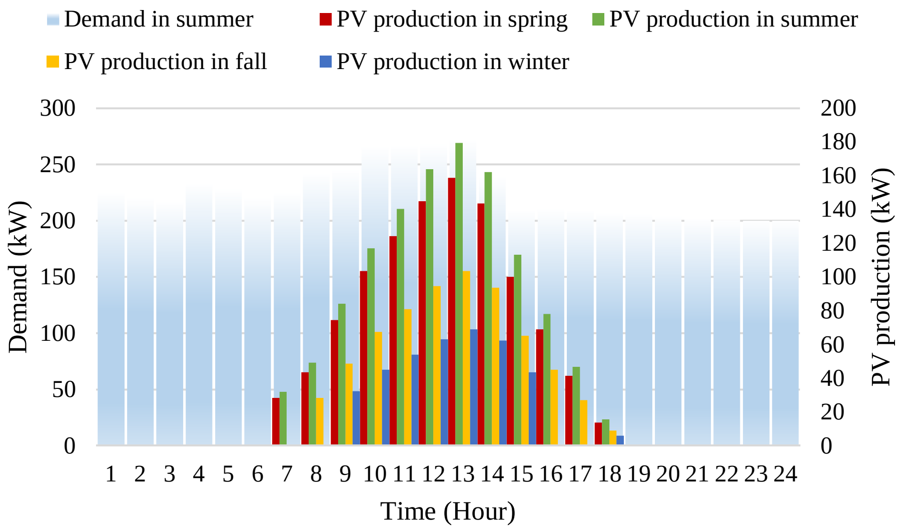
Ramp up/down rates of dispatchable units are less than 1 minute. The maximum fuel available for each generator in the microgrid can be used to produce a total of 400 kWh electrical energy. According to Table 1, in microgrids of type 1, there are three dispatchable generators: No. 1, No. 2 and No. 3 while in microgrids of type 2, there is only one generator of type No.3.

The required data for the battery system is summarized in Table 2. This battery is available in both types of microgrids.

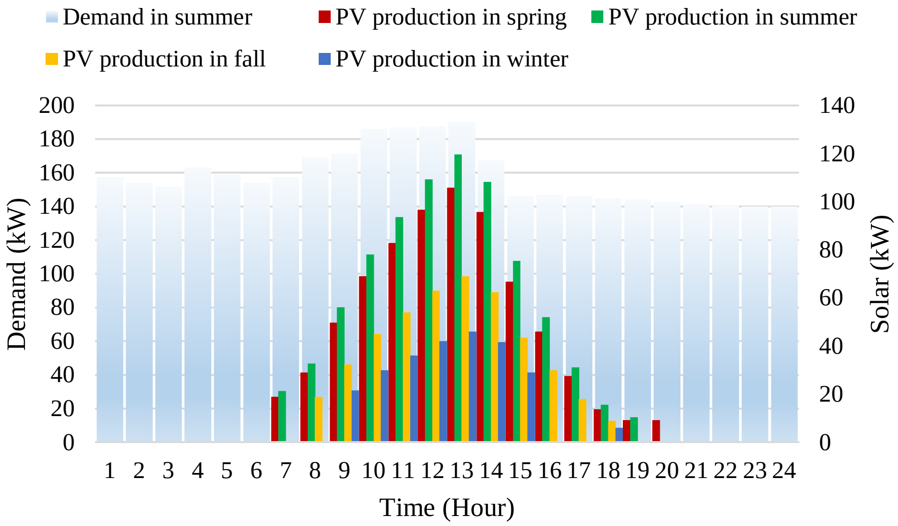
Table 2: Battery characteristic

Capacity (KWh)	Max Charging/Discharging Power (kW)	Min-Max SOC (kWh)	Initial SOC (kWh)	η
100	70-100	0-100	100%=100	0.95

The hourly load profile and solar power generation within microgrids in typical days of different seasons are depicted in Fig. 5. Different load coefficients are used for demand profile adjustment in different seasons as shown in Table. 3.



(A)



(B)

Fig. 5: Demand and solar power profiles in microgrids: A) Type-1 microgrid B) Type-2 microgrid

Table. 3: Peak load for each season in the microgrids

Season	Spring	Summer	Fall	Winter
Load coefficient	0.85	1	0.88	0.8

To handle the stochastic energy management problem in each microgrid, different uncertainties associated with the load demand and renewable generation output are considered. To this end, 500 scenarios are generated initially based on a normal distribution function with 3% and 5% error in demand and solar power predictions, respectively. Then, 10 scenarios are chosen with the backward reduction algorithm. To account for other uncertainties related to fuel arrival time, 5 scenarios with different probabilities are extracted as shown in Table 4. It is assumed that the minimum time of fuel delivery to both types of microgrid is 4 hours. In total, 50 scenarios with different probabilities are produced in order to solve the first sub-problem.

Table 4: Different scenarios for fuel arrival time in all microgrids

$\tau(h)$	4	5	6	7	≥ 8
π_τ	0.4	0.3	0.15	0.1	0.05

PDN and WDN Data:

The maximum active/reactive power demands of PDN and water demand of WSN are depicted in Fig. 6 and these values in each hour of a day is determined based on the 24-hour load multiplier of the PDN and WDN which is illustrated in Fig. 7. It is assumed that the loads in nodes (19-22) are commercial while the rests are residential.

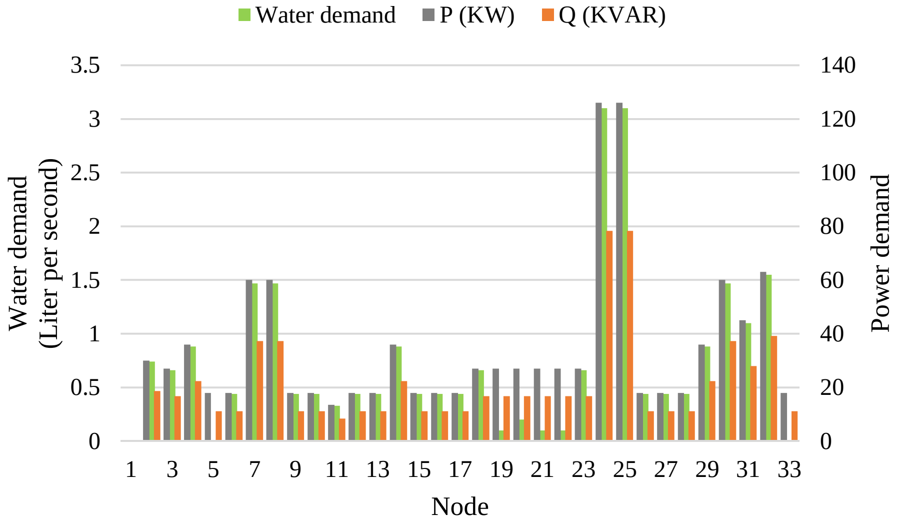


Fig. 6: Water, active and reactive power demands of networks

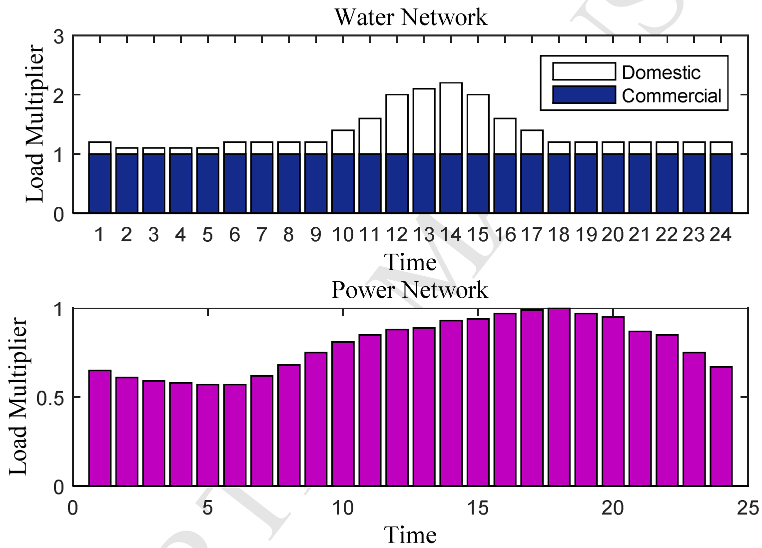


Fig. 7: Load multiplier of PDN and WDN

Value of load inaccessibility to power and water is depicted in Fig. 8. Loads in nodes 5 and 33 of distribution network are water pumps, thus the value of load inaccessibility to water of these nodes is zero. It should be noted that the dynamic value of each water pump for restoration will be determined in the restoration problem. In order to determine the importance of one pump, the accessibility function of loads will be obtained with EPANET and will be compared with the state in which the water pump is restored. The 24-hour load multiplier of the PDN and WDN is illustrated in Fig. 8. Other information about the IEEE 33-bus distribution system can be found in (Baran and Wu, 1989).

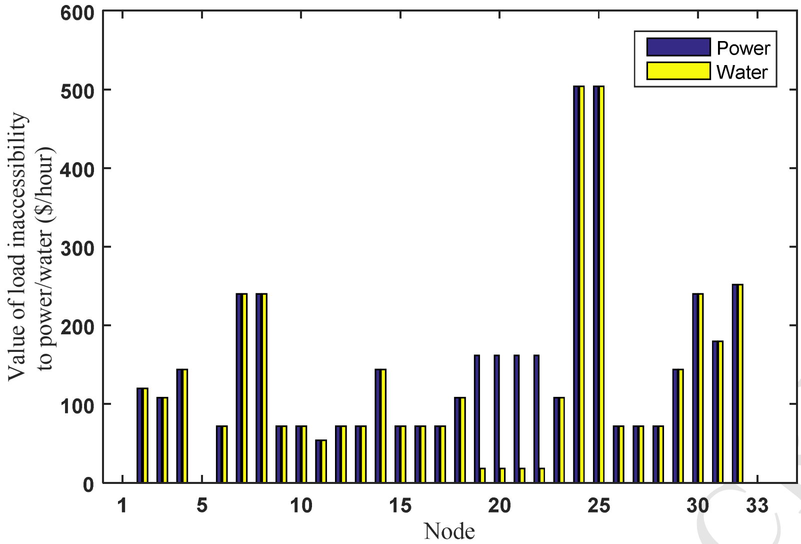


Fig. 8: Value of loads inaccessibility to power and water

The uncertainty of demand in both PDN and WDN is modeled with a normal distribution function with 3% error. According to (Javanbakht and Mohagheghi, 2014; Ma et al., 2018; Ouyang and Duenas-Osorio, 2014), the fragility function of PDN poles ($p_{f,pole}$), main transformer (substation) ($p_{f,sub}$) and conductors ($p_{\mathrm{f,conductor}}$) can be considered as below:

$$\begin{aligned} p_{f,pole}(ws) &= \Phi[\ln((ws)/m_R)/\xi_R] \\ p_{f,sub}(ws) &= \Phi[\ln((ws)/m_R{}')/\xi_R{}'] \end{aligned} \tag{36}$$

where $\Phi[.]$ is lognormal cumulative distribution function with mean and standard deviation m_R and ξ_R respectively. m_R and ξ_R depend on the structure of the pole, $m_R{}'$ and $\xi_R{}'$depend on the local train and structural characteristic of the substation.

$$p_{\mathrm{f,conductor}}(w) = \begin{cases} 0, & ws \le ws_{\min} \\ \dfrac{ws - ws_{\min}}{ws_{\max} - ws_{\min}}, & ws_{\min} \le ws \le ws_{\max} \\ 1, & ws \ge ws_{\max} \end{cases} \tag{37}$$

Where $ws_{\min}$ is the minimum wind speed can damage the conductor and $ws_{\max}$ is the maximum wind speed that damages the conductor certainly.

Hurricane:

According to National Hurricane Center, The intensity of hurricanes is categorized into five groups. The best method to consider the intensity and occurrence time of hurricanes in the study is analyzing the historical data related to the region where the PDN is located. In this paper, it is assumed, the probability of occurrence of a hurricane is 0.8 and 0.2 for categories 1 (74-95) mph and 2 (96-110) mph, respectively. According to Fig. 2, repair time of PDN is another uncertain parameter which is modeled with discrete distribution function as in Table. 5.

Table. 5: Repair time probabilities of PDN

Hurricane category 1					Hurricane category 2				
Hours	4	5	6	7	Hour	6	7	8	9
Probability	0.2	0.3	0.3	0.2	Probability	0.2	0.3	0.3	0.2

Furthermore, the monthly probabilities of hurricane occurrence within a year are obtained from (Li et al., 2016) which is presented in Table. 6.

Table. 6: Monthly probabilities of hurricane occurrence within a year

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Probability	0	0	0	0	0.01	0.03	0.05	0.25	0.38	0.22	0.05	0.01

Candidate strategies:

The characteristics of candidate strategies are explained in Fig. 9.

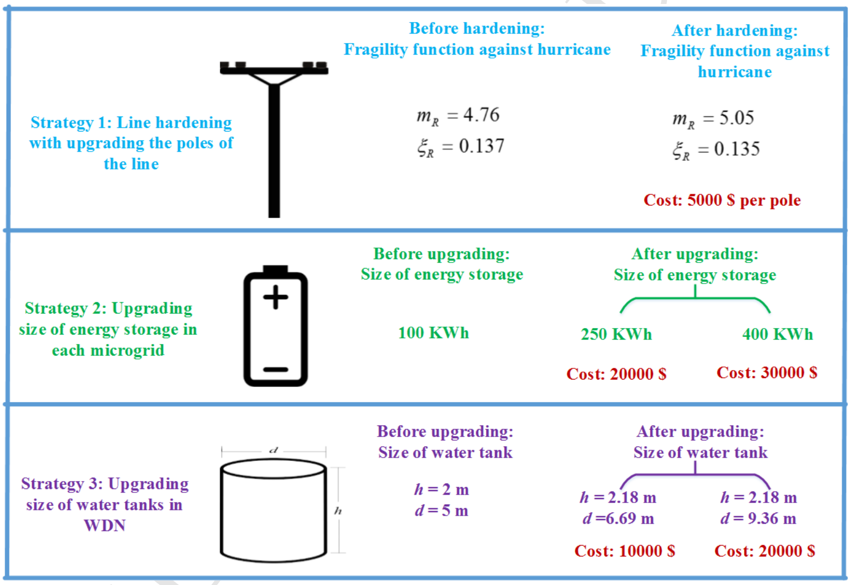


Fig. 9: The characteristic of candidate strategies

Simulation:

Case 1: The simulation is started by analyzing one scenario and investigating the impact of battery energy storages size in microgrids, water tanks size and back-up generators operation in the WDN on the resilience improvement.

It is considered the scenario in which a hurricane with the speed of 91.9 mph in October could cause the outage of lines (7-8), (12-13), (14-15), (16-17), (19-20), (23-24), (30-31) and the main feeder at point of common coupling. The restoration plan will be performed after hurricane at 1 P.M. The repair time of the network (i.e., duration of the emergency period) is 6 hours. Since the PDN is disconnected from the mains, the only way to restore the loads is to incorporate microgrids. To this end, DSO asks microgrids to run the stochastic EMS and announce their contributions in restoration process. The amount of energy that each microgrid can deliver to PDN during emergency period is shown in Fig. 10. According to this Figure, microgrids type 1 can deliver more energy to PDN in emergency conditions compared to microgrids type 2. The restoration problem is solved considering two different sizes of battery in microgrids and the results are depicted in Fig. 11. As the battery size in microgrids in nodes 3 and 29 (type 2) is increased, more loads can be restored. Furthermore, microgrid in node 3 can restore load 5 which is a water pump. Therefore, by increasing the battery size as a clean strategy in some microgrids, the resilience of PDN and WDN will be enhanced. This clean strategy can improve the nature of some microgrids and prepare them as reliable sources for PDN support. Furthermore, with increasing the battery size in some microgrids, it is possible to expand the electrification domain to restore important loads such as a water pump to enhance the resilience of WDN.

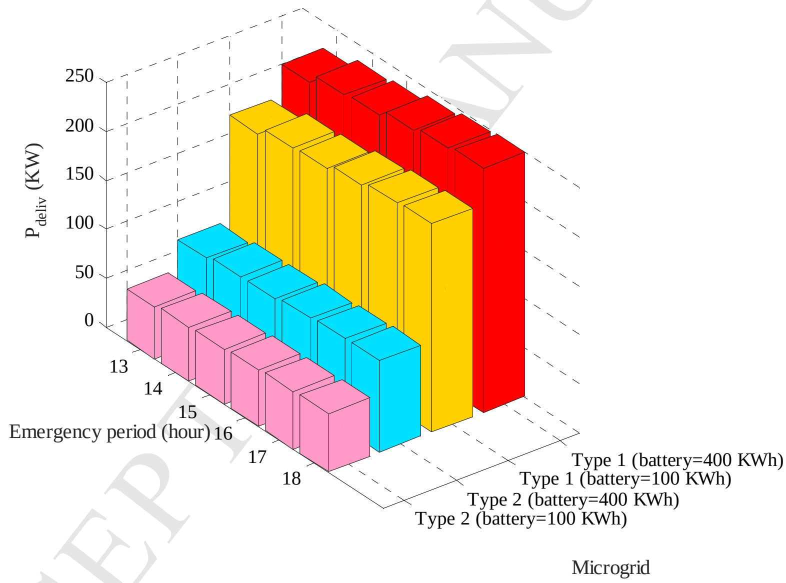
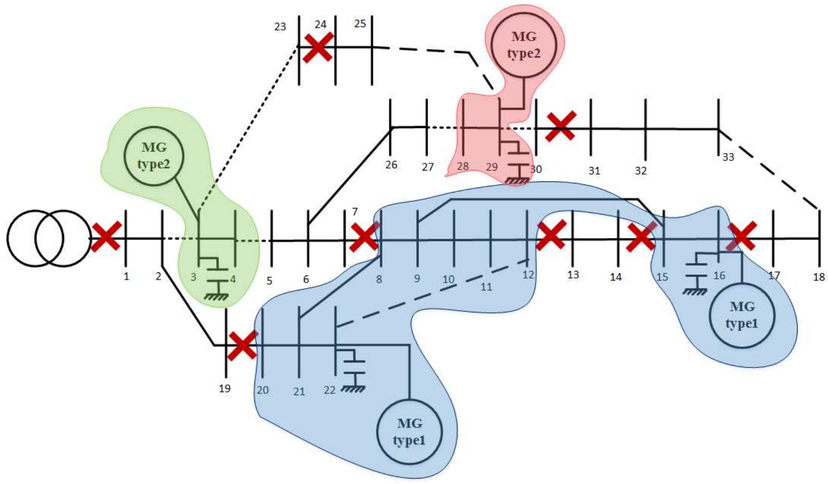
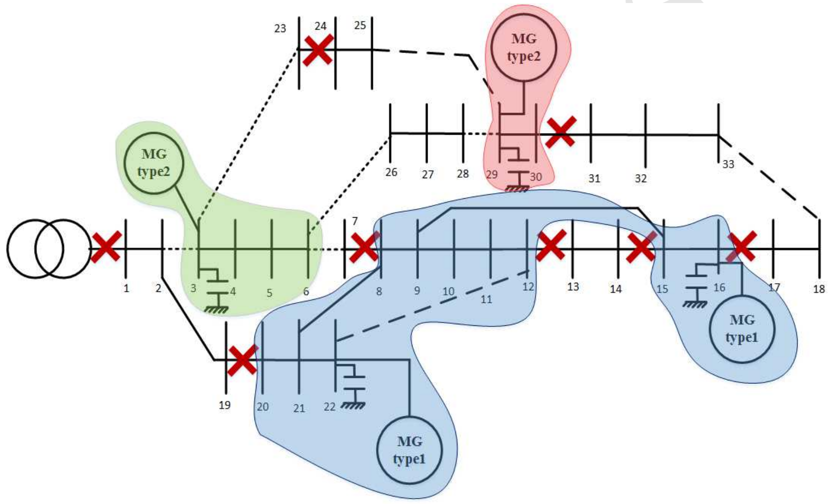


Fig. 10: The amount of energy deliverd by microgrids to PDN in emergency period



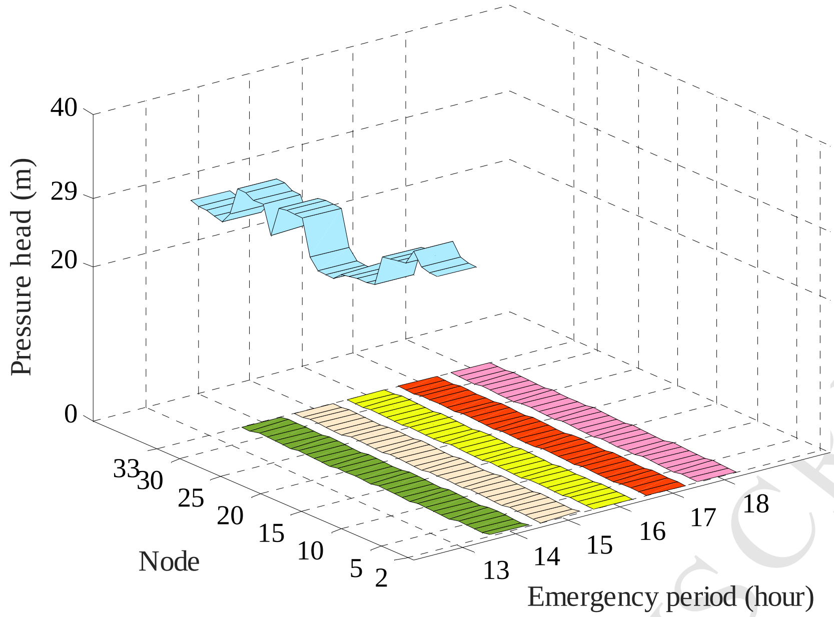
(A)



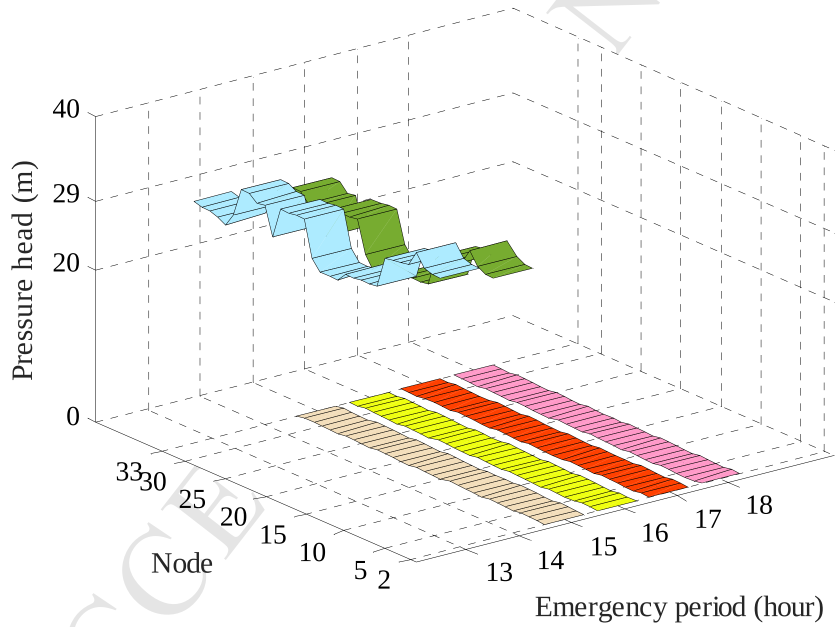
(B)

Fig. 11: The result of restoration problem: A) battery size of 100 kWh in microgrids, B) battery size of 400 kWh in microgrids

Considering the results of restoration plan with the battery size of 100 kWh, it can be observed that none of the water pumps can be restored by microgrids. In this regard, Fig. 12 shows the water pressure at different nodes in WDN considering two different sizes of water tanks without the backup generators for water pumps.



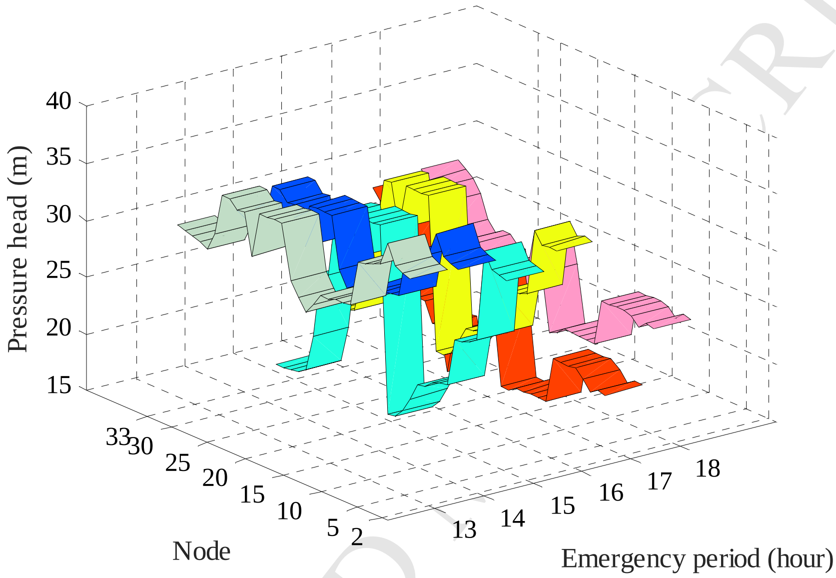
(A)



(B)

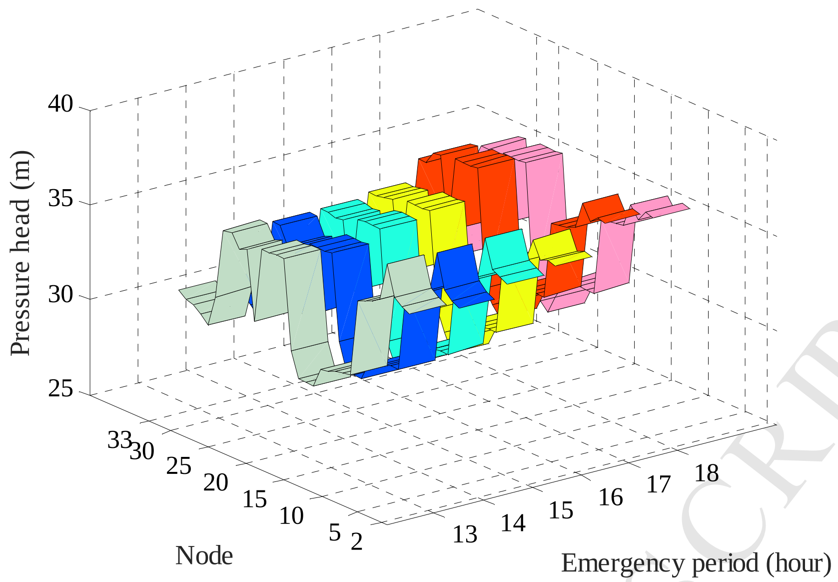
Fig. 12: Water pressure at different nodes: A) tank size: diameter=5m, height= 2m, B) tank size: diameter=9.36m, height= 2.18m

The smaller size of water tanks can provide water for all nodes with an acceptable pressure only for one hour while in the rest of the emergency period, the water demand cannot be met. According to Fig. 12 (B), if the water tanks is sized around four times bigger, the water access will last for two hours in emergency period. In other words, appropriate sizing of the water tanks in WDN as a clean strategy can enhance the resilience of WDN in emergency conditions. This strategy is now investigated when the water pumps are equipped with backup generators. The water pressure at different nodes is depicted in Fig. 13, when each generator can be operated for three hours. In the same figure, the optimal operation of these generators is shown. According to Fig. 13, the water pressure at different nodes are significantly improved with optimal operation of backup generators. In this regard, if the smaller size of water tanks is chosen (diameter=5m, height= 2m), in some hours and at some nodes the water pressure is below the acceptable value. However, with bigger water tanks (diameter=9.36m, height= 2.18m), the water accessibility with acceptable pressure can be guaranteed during the emergency period.



Emergency period (hour)	13	14	15	16	17	18
Gen 1-water pump in node 5	ON	ON	ON	OFF	OFF	OFF
Gen 2-water pump in node 33	ON	OFF	OFF	ON	ON	OFF

(A)

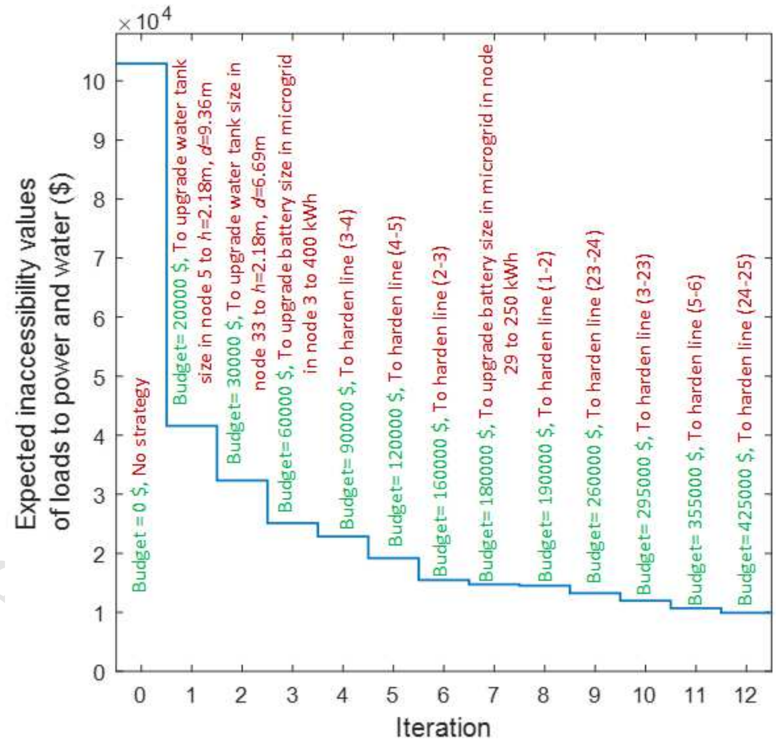


Emergency period (hour)	13	14	15	16	17	18
Gen 1-water pump in node 5	ON	ON	OFF	ON	OFF	OFF
Gen 2-water pump in node 33	ON	OFF	ON	ON	OFF	OFF

(B)

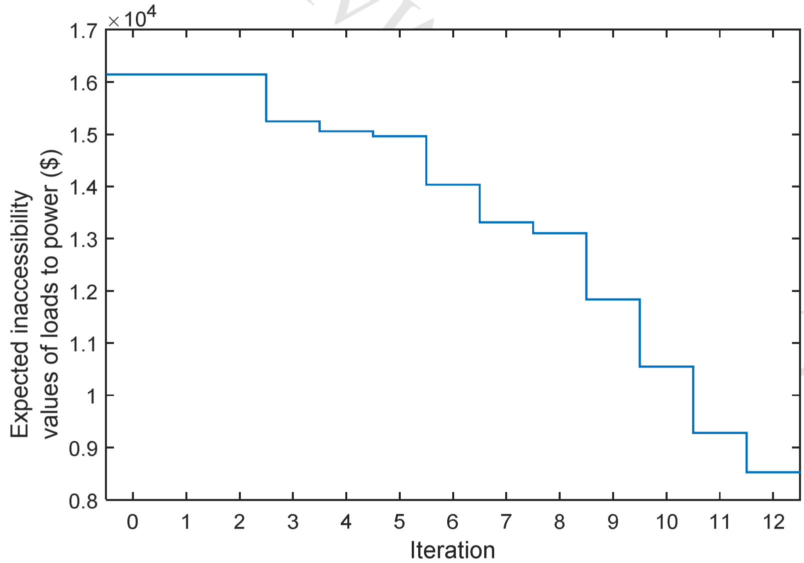
Fig. 13: Water pressure at different nodes when the water pumps are equipped with backup generators: A) tank size: diameter=5m, height= 2m, B) tank size: diameter=9.36m, height= 2.18m

Case 2: After analyzing one scenario and investigating the impact of the two proposed strategies, the resilience improvement planning problem is solved in an uncertain environment. First, 1000 scenarios with regard to the uncertain parameters of PDN, WDN and hurricanes are produced and then 50 scenarios with different probabilities are obtained with backward reduction. Approximately, in 20 % of the final scenarios, the connection between PDN and the substation is damaged. According to Fig. 14, the problem is solved iteratively until the budget limit of 430000 $ is reached. In each iteration of the program, the best strategy is also identified and reported. Iteration 0 shows the expected loads inaccessibility values to power and water under a hurricane before any hardening strategy. According to Fig. 14 (c), despite the available tanks and backup generators with limited fuel for each water pump in the WDN, the dependency of WDN to power outage is high and the value of lost load touches 90000 $. Furthermore, the expected inaccessibility value of loads to power under a hurricane is more than 16000 $. Since the expected inaccessibility of loads to water is more than power, upgrading the size of water tanks in node 5 and 33 respectively to the bigger and smaller candidate sizes is chosen as an action plan in the first two iterations. This strategy can decrease the dependency of WDN operation to PDN significantly.



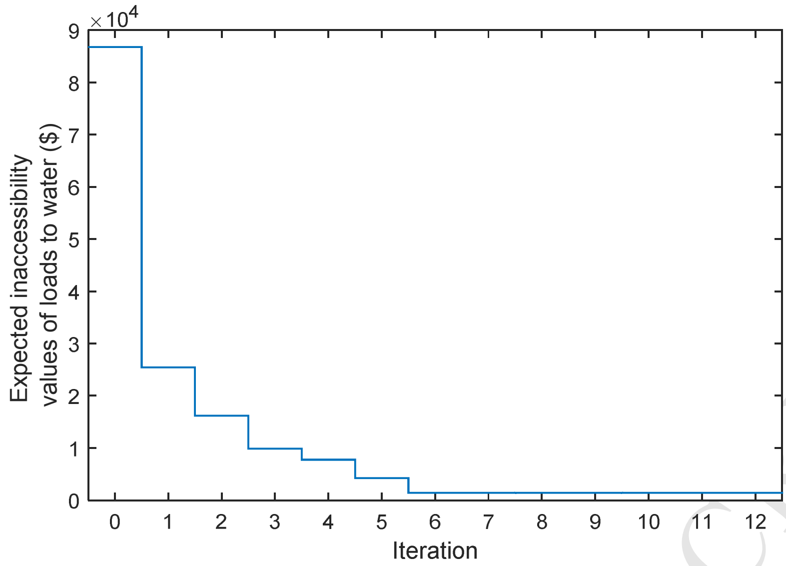
×10^4
Expected inaccessibility values of loads to power and water ($)
Budget = 0 $, No strategy
Budget= 20000 $, To upgrade water tank size in node 5 to h=2.18m, d=9.36m
Budget= 30000 $, To upgrade water tank size in node 33 to h=2.18m, d=6.69m
Budget= 60000 $, To upgrade battery size in microgrid in node 3 to 400 kWh
Budget= 90000 $, To harden line (3-4)
Budget= 120000 $, To harden line (4-5)
Budget= 160000 $, To harden line (2-3)
Budget= 180000 $, To upgrade battery size in microgrid in node 29 to 250 kWh
Budget= 190000 $, To harden line (1-2)
Budget= 260000 $, To harden line (23-24)
Budget= 295000 $, To harden line (3-23)
Budget= 355000 $, To harden line (5-6)
Budget= 425000 $, To harden line (24-25)
Iteration

(A)



×10^4
Expected inaccessibility values of loads to power ($)
Iteration

(B)



(C)

Fig. 14: The results of the resilience improvement planning against hurricane in Case 2: A) Expected loads inaccessibility values to power and water, B) Expected loads inaccessibility values to power, C) Expected loads inaccessibility values to water

During the third iteration, the battery size in microgrid in nodes 3 is upgraded to the bigger candidate size. By doing this, microgrid in nodes 3 can expand its electrification domain and restore more loads and water pumps which in turn enhances the resilience of PDN and WDN, simultaneously. In the next steps, the most important lines are chosen to be hardened. The importance of each line is determined based on its loading, length and the failure rate. For example, the candidate lines (1-2),(2-3),(3-4),(4-5),(5-6) for hardening are located in the main network where more power need to be transferred over longer distances. Furthermore, lines (3-23),(23-24) and (24-25) are chosen to be hardened as they distribute the power between the two biggest loads at nodes 24 and 25. In iteration 7, the size of battery in microgrid 29 is chosen to be upgraded. Finally, it is observed that by allocating more budget, the PDN and WDN will be more robust against hurricanes and the expected inaccessibility values of loads to power and water under a hurricane will be decreased, significantly. The amount of budget that the planner wants to spend on resilience improvement will depend on the region where the networks are located and expected rate of hurricanes occurrence.

Case 3: This case study investigates the impact of the proposed clean strategies on resilience improvement of PDN and WDN with changing the vulnerability rate of substation against hurricanes. The proposed model is solved again with 100,000 $ as budget constraint for two different conditions which are: 1) substation is not vulnerable against any hurricane. In other words, substation is damaged in none of the scenarios. 2) Substation is damaged in all the scenarios. The results are shown in Tables 7 and 8, respectively.

Table 7: The Results of the resilience improvement planning in Case 3 (when substation is damaged in none of the scenarios)

Iteration	Strategy	EP[(1)] ($)	EW[(2)] ($)	EPW[(3)] ($)	Cost($)
0	No strategy	14883.5	67978.8	82862.3	0

1	To upgrade water tank size in node 5 to *h*=2.18m,*d*=6.69m	14883.5	42774	57657.5	10000
2	To harden line 2-3	13556.6	26241.9	39798.5	40000
3	To harden line 1-2	13303.8	23881	37184.8	10000
4	To harden line 3-4	13069.6	16798.3	29867.9	30000
	sum				**90000**

(1)EP: Expected loads inaccessibility value to power
(2)EW: Expected loads inaccessibility value to water
(3)EPW: Expected loads inaccessibility value to power and water

Table 8: The Results of the resilience improvement planning in Case 3 (when substation is damaged in all the scenarios)

Iteration	Strategy	EP($)	EW($)	EPW($)	Cost($)
0	No strategy	20587.4	131956.2	152543.6	0
1	To upgrade water tank size in node 5 to *h*=2.18m,*d*=9.36m	20587.4	38605	59192.4	20000
2	To upgrade water tank size in node 33 to *h*=2.18m,*d*=9.36m	20587.4	24663.1	45250.5	20000
3	To upgrade battery size in microgrid in node 3 to 400 kWh	18544.2	12004	30548.8	30000
4	To upgrade battery size in microgrid in node 29 to 400 kWh	17541.2	11294	28835.2	30000
	sum				**100000**

According to Table. 7, when the substation is not vulnerable and it is available as the main energy source for PDN, most of the chosen strategies are line hardening. In iteration 1, unlike Case 2, the water tank size in node 3 is upgraded to a smaller candidate water tanks as a reliable power source is available for water pumps. In the next iterations, most important power lines which are the link of PDN and the substation are chosen to be hardened. With these strategies, the path between PDN and substation becomes more robust again hurricanes. It should be noticed according to Fig. 1, although line 1-2 is more important than line 2-3, this line is chosen to be hardened after line 2-3. The reason is that line 2-3 is longer than line 1-2, so the failure probability of line 2-3 is relatively higher than line 1-2 in hurricanes.

When substation is vulnerable against hurricanes, the inaccessibility values of loads to power and water are increased nearly 39% and 95%. To decrease the dependency of WDN on PDN in this condition, according to Table 8, size of both water tanks is upgraded initially. With this two strategy, the accessibility of loads to water is significantly improved. Microgrids, as the only energy sources in this condition, can restore the disconnected loads. Therefore size of batteries in microgrids in node 3 and 29 are upgraded to 400 kWh in the next step. With this choice, microgrids can expand their borders and restore more disconnected loads and water pumps.

Case 4: This case investigates the impact of microgrids on the environmental and emission concerns compared to the fuel-based DGs which were implemented in previous works. To this end, the contribution of fuel-based generators to produce energy during emergency conditions resulted from hurricanes in two states are considered as follow: 1) Similar to previous works, it is assumed that fuel-based DGs with different capacities equal to the amount of each microgrid can deliver energy to PDN and restore disconnected loads; 2) Microgrids are implemented to restore the disconnected loads as shown in Cases 2 and 3. It should be noted that the reduction of expected energy produced by fuel-based generators is equal to emission reduction. Table. 9 shows the expected energy produced by fuel-based generators in Cases 2 and 3 when microgrids or fuel-based DGs are implemented to restore the disconnected loads.

Table 9: Comparison between microgrids and fuel-based DGs on emission reduction

	Before resilience improvment planning			After resilience improvment planning		
	Fuel based DGs are implemented to restore the disconnected loads	Microgrids are implemented to restore the disconnected loads	Reduction Rate (%)	Fuel based DGs are implemented to restore the disconnected loads	Microgrids are implemented to restore the disconnected loads	Reduction Rate (%)
Case 2: Substation was vulnerable in 20% of scenarios	X [(1)] =5183.5	X=3986.6	23.1	X=5429.2	X=3987.9	26.6
Case 3a: Substation was vulnerable in none of the scenarios	X =5183.5	X=3986.6	23.1	X =5183.5	X=3986.6	23.1
Case 3b: Substation was vulnerable in all the scenarios	X =5183.5	X=3986.6	23.1	X=5499	X=3987.2	27.5

[(1)]X=Expected energy produced by fuel-based generators (kWh)

According to Table. 9, before resilience improvement and only when the microgrids with hybrid energy sources (instead of fuel-based DGs) are implemented to restore the disconnected loads, the expected energy produced by fuel-based generators will decrease by 23.1%. This amount of fuel consumption reduction that mitigates the total emission is highly recognized in emergency conditions resulted from hurricanes. As can be observed, when the size of batteries in microgrids (as a clean energy source) is upgraded to enhance the resilience in different cases, the dependency on fuel-based generators is further decreased. This can be clearly understood in case 3b where the batteries in microgrids in nodes 3 and 29 are resized to 400 kWh and the expected energy produced by fuel-based generators is decreased by 27.5%.

5. CONCLUSION

In this paper, a comprehensive model based on a main problem and two sub-problems for resilience improvement planning of PDN and WDN with multiple microgrids was proposed. The main problem in our resilience improvement studies was configured to minimize the expected inaccessibility value of loads to power and water against hurricanes as well as the investment cost of strategies in presence of uncertain parameters including the time of occurrence and intensity of hurricanes, PDN and WDN demands, power lines operational status against hurricanes and repair time of PDN. In analyzing each scenario of the main problem, the microgrids were modeled as energy sources through the first sub-problem and possible operation of back-up generators for water pumps restoration were included in the second sub-problem. Three clean and effective candidate strategies were proposed to enhance the resilience. The first strategy was upgrading the battery size in microgrids to restore loads and water pumps so as to enhance the resilience of PDN and WDN. The second strategy was identified as upgrading the water tank size in WDN to decrease the dependency of PDN operation to power outages. Line hardening was the third strategy that decreased the failure probability of a power line against hurricanes.

Numerical studies illustrated the effectiveness of the proposed strategies for improving the resilience of PDN and WDN. By investigating the dependency of WDN on PDN, the size of water tanks were upgraded. Microgrids as energy sources in different places of PDN expanded their borders and restored disconnected loads. When the vulnerability of the main source (substation) was high, batteries in microgrids were upgraded to bigger sizes. If the expanded borders of microgrids could also cover the water tanks, this strategy was also effective to enhance the accessibility of loads to water. Line hardening was the other efficient strategy for improving the resilience of PDN and WDN. Especially, resilience could be improved by hardening the path between PDN and the substation, the path between water tanks and energy sources and also the path between important loads and energy sources.

Simulation results also demonstrated that implementing microgrids as cleaner energy sources instead of fuel-based DGs for restoring the disconnected loads could highly decrease the expected energy (thus pollutant emissions) produced by fuel-based generators. This contribution toward a greener environment was better highlighted when batteries in microgrids were upgraded to bigger sizes.

It this paper, it was also assumed that the DSO owns microgrids. Additional work will be required to investigate such subject matter from different ownership perspectives. To this end, the future efforts will be mainly dedicated to expand the proposed model for resiliency improvement of subsystems owned by different entities where interactions should be formed, conflicting objectives have to be met and privacy must be preserved.

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- Clean strategies are proposed to enhance the resilience of power-water networks.
- Microgrids as emergency sources are considered for load restoration.
- Back-up generators of disconnected water pumps are scheduled in emergency conditions.