Sustainable Cities and Society 39 (2018) 592–604

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Power distribution system improvement planning under hurricanes based on a new resilience index

Javad Najafi[a], Ali Peiravi[a,*], Josep. M. Guerrero[b]

[a] Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Department of Energy Technology, Aalborg University, Aalborg, Denmark

ARTICLE INFO

Keywords:
Distribution system planning
Natural disasters
Power system restoration
Resilience
Water network

ABSTRACT

Natural disasters such as hurricanes damage power distribution systems by low probability- high impact events. Other infrastructures such as water networks will be disrupted due to their dependency on the power network. In this situation, a city or region experiences critical conditions. In this paper, a new resilience index based on social welfare concept is presented to decrease unserved loads, restore the distribution system rapidly and decrease the dependency of water network operation to power network failures. The new resilience index is optimized with effective strategies including: upgrading distribution poles, DG placement with different capacities and distribution system automation. The problem is formulated as a stochastic two-stage optimization. The first-stage decisions are the number of each resilience improvement strategy limited to a predetermined budget. Genetic algorithm is applied to solve the first stage. The objective of the second stage is maximizing the social welfare which is solved by an innovative approach. Numerical simulations are performed on the IEEE 33-bus radial distribution system and designed water network related to it. The results demonstrate the effectiveness of the proposed method.

1. Introduction

Human life strongly depends on electricity. This dependency will increase during and after natural disasters. Therefore, a few minutes outage in a power systems can cause the worse events. Over the past 20 years, the number of occurrence of natural disasters' has increased.

Natural disasters impose heavy costs in different parts of the society. Between 2008 and 2012 in the US, the annual damage cost of power outages due to bad weather conditions was between \$25 billion to \$70 billion. The lost economic cost of the US only from Hurricane Sandy was \$14-\$26 billion. The 2011 flood damage costs in Thailand were \$285 million in the power sector and \$180 million to recover and reconstruct the network (Brown, Wang, & Page, 2016).

Other infrastructures such as water and telecommunication depend on electricity and power network outages can disrupt their operation. Several natural disasters that have occurred prove this. The loss of water supply in New York City was due to Hurricane Sandy in 2012 (Zhang, Yang, & Lall, 2016). Many telecommunication site outages in Maule and Tohoku were due to earthquakes in 2010 and 2012, respectively (Krishnamurthy, Kwasinski, & Dueñas-Osorio, 2016).

There is not a universal definition for resilience. One of the comprehensive definitions is according to the National Academy of Science. Resilience is "*the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*" (T. N. A. of sciences, 2012). A system is absorptive if with minimal effort, it can automatically absorb the effects of bad events and minimize the consequences. Recoverability is property of a system that refers to reaction and recovering of the system in minimum time. The adaptive capacity is the ability of the system to organize its components in a targeted manner and without the aid of external factors (Tran, Balchanos, Domercant, & Mavris, 2017).

A resilient power system must have the ability to recover the network with an effective and rapid restoration program against several faults such as multi-lines outages (Gholami, Aminifar, & Shahidehpour, 2016). The properties of these faults are low probability but high impact such as faults due to natural disasters. Enhancing the resilience of power systems not only decreases the outage power costs, but it also increases social welfare (President's Council of Economic Advisers and the U.S. Department of Energy's Office of Electricity and Energy Reliability, 2013). For resilience enhancement, first, there must be an efficient framework to quantify the resilience of a power system according to the level of power in which the study is done. First it is necessary to identify the fragility of the elements of that level such as transmission lines, towers or poles and conductors. Fragility function is

* Corresponding author.
E-mail addresses: javad.najafi@mail.um.ac.ir (J. Najafi), peiravi@um.ac.ir (A. Peiravi), joz@et.aau.dk (J.M. Guerrero).

https://doi.org/10.1016/j.scs.2018.03.022
Received 2 December 2017; Received in revised form 19 March 2018; Accepted 22 March 2018
Available online 27 March 2018
2210-6707/

Nomenclature

Indices and Sets

i, j Load (bus) indexes
BS_i Buses set which are connected to bus i
s Scenario index
l Power distribution lines index
pl Power distribution pole index
c Power distribution conductor index
m Power network (main network or each intentional islanded microgrid) index
g DG (backup generator) index

Parameters and Constants

α_i Power importance coefficients for load i
β_i Water importance coefficients for load i
LI_i Load importance coefficient of load i
N_{load} Number of loads
N_{line} Number of lines in power distribution network
N_{pl}^l Number of poles of line l
N_c^l Number of conductors of line l
w_s Speed of hurricane in scenarios
$w_{\min}$ Minimum wind speed that can damage the conductor
$w_{\max}$ Maximum wind speed that certainly damage the conductor
$\rho(s)$ Probability of each scenario
S Number of scenarios
C_l^H Cost of hardening line l
C^{DG} Cost of DG per KW
N_b Number of buses in power network
C^{RS} Cost of each manual switch being upgraded to be controlled remotely
B Amount of budget constraint
G_{ij} Line conductance between bus i and j
B_{ij} Line susceptance between bus i and j
$|V_{\min}|$ Minimum allowable voltage magnitude in the network
$|V_{\max}|$ Maximum allowable voltage magnitude in the network
$|I_{ij}^{\max}|$ Maximum current magnitude between bus i and j
$P_{DG_g}^{\max}$ Maximum output active power of DG g
$Q_{DG_g}^{\max}$ Maximum output reactive power of DG g
$P_{DG_{g,i}}^{\max}$ Output maximum active power of DG g which is located in bus i
$Q_{DG_{g,i}}^{\max}$ Output maximum reactive power of DG g which is located in bus i

Functions and variables

LSF_i Satisfaction function of load i
PA_i Power access function of load i
WA_i Water access function of load i
RI Resilience index
SRI_1 First sub resilience index
SRI_2 Second sub resilience index
SRI_3 Third sub resilience index
$p_{f,pole,pl}$ Fragility function of pole pl
$p_{f,cond,c}$ Fragility function of conductor c
$OF1$ Objective function of the first stage
X_l a binary variable which determines line l is hardened or not
X a binary variable which determines bus i is equipped to a DG or not
cap_i^{DG} Capacity of DG (KW) which is located at bus i
$N_{M\rightarrow R}$ Number of manual switches that are being upgraded to be controlled remotely
$OF2$ Objective function of the second stage
M_s Number of power networks (main network or intentional islanded microgrid) in scenario s
$N_b^{m,s}$ Number of buses in network m in scenario s
$N_{line}^{m,s}$ Number of lines in network m in scenario s
$G^{m,s}$ Number of DGs in power network m in scenario s
$\theta_{ij}^{m,s}$ Difference phase voltage angle between bus i and j in network $m$in scenario s
$P_i^{m,s}$ Active power of the load at bus i in network $m$in scenario s
$Q_i^{m,s}$ Reactive power of the load at bus i in network m in scenario s
$|V_i^{m,s}|$ Voltage magnitude at bus i in network m in scenario s
$|I_{ij}^{m,s}|$ Current magnitude between bus i and j in network m in scenario s
$P_{loss,l}^{m,s}$ Active power loss of line l in network $m$in scenario s
$P_{DG_g}^{m,s}$ Active power of DGg in network m in scenario s
$Q_{loss,l}^{m,s}$ Reactive power loss of line l in network m in scenario s
$Q_{DG_g}^{m,s}$ Reactive power of DGg in network m in scenario s

the probability of failure of a structure or structural component vs. the intensity of a hazard such as wind speed (Panteli, Pickering, Wilkinson, & Dawson, 2017). Most of the previous works such as (Espinoza, Panteli, Mancarella, & Rudnick, 2016; Panteli and Mancarella, 2015; Liu et al., 2016; Arab, Khodaei, Han, & Khator, 2015a; Arab et al., 2015b) study the resilience assessment or enhancement of power systems in the transmission level. Some works such as (Brown, Carlyle, Salmeron, & Wood, 2006; Bier, Gratz, Haphuriwat, Magua, & Wierzbicki, 2018; Yuan, Zhao, & Zeng, 2007; Arroyo and Francisco, 2013) have investigated the vulnerability of transmission networks against natural disasters or terrorist attacks with different models. In other words, these works try to identify the most critical lines in a transmission network that with whose outage, the transmission network will experience the maximum load loss. In some works such as Bier et al. (2018); Yuan et al. (2007), the critical lines are hardened considering a budget constraint. According to (President's Council of Economic Advisers and the U.S. Department of Energy's Office of Electricity and Energy Reliability, 2013), about 90% of faults during storms occur in distribution systems. In Ouyang and Duenas-Osorio (2014), a probabilistic framework for quantifying the resilience of Harris County, Texas power network considering both transmission and distribution networks is presented. This model includes DC power flow for power system performance that ignores the voltage of nodes.

The impact of wind storms on reliability of distribution systems is investigated in Li, Zhang et al. (2014). For distribution system operation analysis, the minimal path set concept is used to determine the state of loads after outages. A main difference between reliability and resiliency is that in reliability assessment, only the frequency and duration of outages are calculated with reliability indices such as SAIDI and EENS, but resilience deeply investigates the system operation before, during and after extreme events (Li, Shahidehpour, Aminifar, Alabdulwahab, & al-Turki, 2017). In other words, resiliency studies the system operation from the occurrence of a disturbance until complete recovery of the system and it is important that the system recovers in minimum time.

There are various strategies for increasing the resilience of power systems. Hardening is one of the usually expensive strategies that increases resilience. Hardening is physical changes in network infrastructure to make it less vulnerable to extreme events (Bie, Lin, Li, & Li, 2017). Hardening has different strategies and if the resilience of power system increases with hardening, it is important that the best hardening strategy is implemented. A hardening strategy such as undergrounding the overhead power lines enhances the resilience of the power system against hurricanes. However, this strategy decreases the resilience against floods. Distribution automation is another strategy that enhances the resilience of distribution systems. There are different devices that can help the distribution system to operate rapidly such as remote fault indicator for decreasing the fault detection time and remote control switches for decreasing the opening and closing times of switches (Chen, Wang, & Ton, 2017). Distributed generation units are appropriate options for increasing the resilience of distribution systems after natural disasters. In Chen, Wang, Qiu, and Zhao (2015), each DG forms a microgrid to restore critical loads. Unlike (Chen et al., 2015), in Wang, Li, and Li, 2017) loads can be restored with intentional islanding including multiple DGs. The DGs which are used in this study are fossil fuel based combustion generators. These generators are widely used as backup generators to restore disconnected loads after natural disasters (Chen et al., 2015). The output of these generators does not depend on weather conditions unlike other DGs such as wind or PV.

Microgrids are small power networks including DGs such as wind, solar and energy storage units that can operate islanded or connected to the main network. Li, Ma et al. (2014) implement microgrids like DGs that are for load restoration after faults in distribution system. In Gao, Chen, Xu, and Liu (2016); Xu, Liu, Schnieder, Tuffner, and Ton (2018), the microgrids are used to restore the critical loads after natural disasters. Stability and duration time of microgrid operation are investigated in Gao et al. (2016); Xu et al. (2018). According to Che, Khodayar, and Shahidehpour (2014), during March 2011 earthquake and tsunami in Japan, the Sendai microgrid operated for two days in an islanded mode. Demand response, advanced automation and self-healing are other options that can improve the resilience of power systems (Fotuhi-Firuzabad et al., 2016).

Only a few research studies have been devoted to resilient enhancement of distribution systems.

Most of the distribution systems are designed radially and there are some normally opened switches or tie-line switches that can change the configuration and restore the system. As it is mentioned before, a rapid restoration program should be prepared for distribution networks. Most of the restoration programs are designed for N-1 or N-2 outages while the number of outages due to natural disasters is more than two. The Modified Viterbi algorithm is proposed in Yuan, Illindala, and Khalsa (2017) to restore the distribution system. This algorithm is like dynamic algorithms whereby in each stage one of the tie switches should be closed until maximum of the loads are restored.

Budget is the main constraint that forces the planner to choose cost-effective strategies for improving the resilience of distribution systems.

Yuan et al. (2016) solve a robust two-stage model for resilient distribution planning problem. In other words, with a budget constraint, load shedding is minimized for the worst case attack that is a natural disaster. The candidate resilient enhancement strategies in Yuan et al. (2016) are hardening the distribution lines and placement of DGs. In Yuan et al. (2016), each line which is hardened will no longer be vulnerable against natural disasters. In addition, the budget constraint is modeled in such a way that a determined number of lines and numbers of DG can be hardened and placed, respectively. For other combinations of the number of DGs and lines, the problem should be solved again. The line outage number is pre-determined like the N-K concept.

Ma, Chen, and Wang (2018) in a bi-level model solve the resilient distribution system planning with different strategies including vegetation management and upgrading poles. In the lower level, the most critical lines are identified and in the upper level, the hardening strategies are chosen. Unlike Yuan et al. (2016) in Ma et al. (2018), a hardened line has a low failure probability not zero. In Ma et al., (2018), it is assumed that the repair time is the same for all outaged lines and all of the outaged lines are repaired simultaneously.

Chen (2016) proposed a two-stage stochastic model for enhancing the resilience of distribution systems with line hardening strategy. The objective of the lower level is to minimize load shedding of each scenario and the objective of the higher level is to minimize the expected value of the lower level objective. The duration time of system operation analysis in Chen (2016) is 24 h. This means that if the time repair of outage lines is more than 24 h, the full recovery of the distribution system is not studied.

The key contributions of this paper include:

- A new resilience index based on social welfare is proposed. The resilient distribution system planning problem and restoration problem are solved in such a way that decreases the dependency of operation of water network to power network failures and the aim is that most of the loads access to power and water rapidly after natural disasters.
- For accurately investigating water network operation, the water network is modeled in EPANET.
- An innovative approach is proposed for restoration of distribution systems.
- Multiple strategies which are appropriate for resilience improvement are implemented.

The rest of the paper is organized as follows: Section two provides problem formulation. Section three explains how the problem is solved. Numerical results are presented in section four and section five concludes the paper.

2. Problem formulation

In this section, the new resilience index and strategies for resilience improvement are introduced and the model for enhancing the resilience of distribution system is provided.

2.1. Resilience index based on social welfare concept

Water and power are vital for all loads and customers. Without each one of them, the performance and satisfaction of loads or customers will decrease. The water network depends on the power network. Without electricity, the water pumps cannot deliver water to consumers. So, this dependency of water network to power network must be considered in different areas. The dependency of water network to power network is different and it depends on water network structure. According to Fig. 1, it is assumed that the water of the consumers is supplied with several pumps and the electricity of each pump is supplied with different buses of the distribution system.

The importance and operation time of each pump are different and this issue should be considered. Maybe some of the water pumps are equipped with emergency power. However, the time in which the

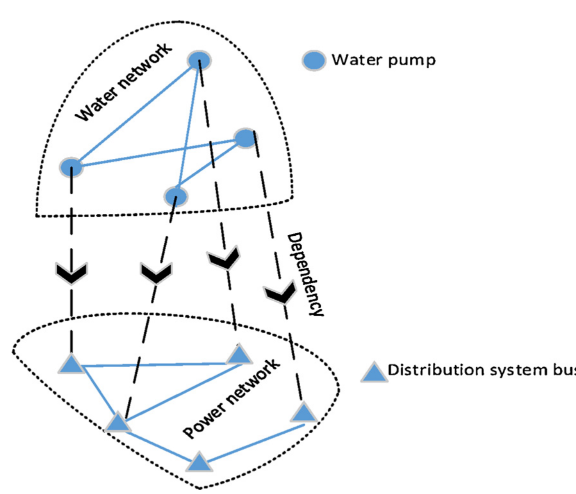

Fig. 1. A schematic of power and water network.

emergency power can supply electricity for the pumps is usually shorter than the power network outage time due to natural disasters.

In this paper the satisfaction function is defined for each load as shown in (1) which indicates social welfare based on load access to power and water.

$$LSF_i = \alpha_i PA_i + \beta_i WA_i \tag{1}$$

α_i and $\beta_i$are defined for each load such that $\alpha_i + \beta_i = 1$.

PA is a binary function that indicates the state of loads in the power distribution system.

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

WA is the water accessibility function in water network and is illustrated in Fig. 2. If the water pressure in a node is higher than the Min pressure, the water satisfaction of that node is 1.

So the value of *LSF* for each load is in range of 0–1. α and β for each load must be selected carefully. These parameters may be different for two domestic or commercial loads. More work could be done on this, but in this paper, for domestic and commercial loads α and β are assumed to be equal to 0.5, 0.5 and 0.9, 0.1, respectively.

The measurement of performance (MoP) of this study is the social welfare of all loads which is normalized in range of 0–1 as Eq. (3).

$$MoP = \sum_{i=1}^{N_{load}} LI_i LSF_i \tag{3}$$

It is be noticed that $\sum_{i=1}^{N_{load}} LI_i = 1$.According to Fig. 3, the maximum social welfare is achieved when power and water are available for all loads or customers. Upon the occurrence of natural disasters, the social welfare is decreased due to distribution system faults such as line outages. In this circumstance, if the distribution system nodes that supply the water pumps are disconnected, the water pumps stop to work and the water network cannot delivers water to the consumers. So the water and power are not available for some loads. It is be noticed that according to Fig. 3, the social welfare reduction starts at t_0 and can be occurred in several steps. At t_2, the restoration is performed with tie lines and the social welfare of the system is increased, but yet the system has not recovered completely. The failed distribution lines will be repaired and operated step by step and the social welfare also increases step by step. At t_{FR} the social welfare of the system will go back to its initial state (maximum level).

According to Fig. 3, the resilience is formulated in (4)–(7).

$$RI = SRI_1 + SRI_2 + SRI_3 \tag{4}$$

$$SRI_1 = R_{\min} \qquad 0 \le SRI_1 \le 1 \tag{5}$$

$$SRI_2 = \frac{\int_{t_0}^{t_{ER}} MoP(t)dt}{t_0 \times t_{ER}} \qquad 0 \le SRI_2 \le 1 \tag{6}$$

$$SRI_3 = \frac{t_{\min}}{t_{FR}} \qquad 0 \le SRI_3 \le 1 \tag{7}$$

All of the sub resilience indices are normalized in the range of 0–1. SRI_1indicates the robustness of the system. $R_{\min}$ is the minimum social welfare. Recoverability of the system in a predetermined time is calculated by SRI_2. t_{ER} is the expected time for restoration of the network that is different for each category of hurricane. SRI_3 shows the rapidness of system recovery. $t_{\min}$ is the minimum interval time that performance as social welfare can be enhanced.

2.2. Proposed strategies for resilience improvement

In this paper, different strategies include line hardening (upgrading the distribution poles), distribution automation (full or partial) and DG placement (different level capacity) are proposed to enhance the resilience of distribution system. It is possible that DGs can expand their borders and restore another disconnected loads. Full distribution automation strategy upgrades all the manual line switches to remote control switches but partial distribution automation strategy upgrades only the tie line switches.

2.3. Stochastic two-stage model for improving the resilience of distribution system

In this section, first, the scenarios generation is explained and then the proposed model is formulated.

2.3.1. Scenarios generation

In this study, operation state of distribution power lines against hurricane, hurricane occurrence time, power distribution network load demand (active and reactive) and water network demand are assumed uncertain sets that are considered in scenarios generation. Scenario generations are depicted in Fig. 4.

2.3.1.1. A. Model of operation state of distribution power lines against hurricane and hurricane occurrence time. In distribution systems, overhead power lines are exposed to bad weather conditions (Brown, 2009). An overhead power line can be damaged by hurricanes due to two reasons: poles toppling and conductors tearing. The fragility function of poles and conductors in Ouyang and Duenas-Osorio (2014) and Javanbakht and Mohagheghi (2014) are used in this paper and are given bellow.

$$p_{f,pole,pl}(w_s) = \min\{0.0001e^{0.0421w_s}, 1\} \tag{8}$$

$$p_{f,cond,c}(w_s) = \begin{cases} 0, & w \le w_{\min} \\ \frac{w - w_{\min}}{w_{\max} - w_{\min}}, & w_{\min} \le w \le w_{\max} \\ 1, & w \ge w_{\max} \end{cases} \tag{9}$$

In scenario generation, first it is necessary to study the history of occurrence of hurricanes in the region of the distribution system. The hurricane occurrence model should be provided but this is out of the scope of this paper. Hurricanes are categorized into five groups based on their speed (Saffir-Simpson Hurricane Wind Scale, 2017). In this paper, hurricanes in category 1–4 will be considered. It is assumed that for each scenario the hurricane occurs with different speeds based on the probability for each category of hurricanes history in the region. The time that each hurricane occurs is randomly chosen during a day. For each scenario with different wind speed and time of occurrence, the state operation of poles and conductors of each lines is obtained with comparing a random number and failure probability which is calculated with the fragility function. So, the state of each distribution lines is determined. The repair time of each line outage is obtained based on the number of poles and conductors that are damaged and their repair time.

2.3.1.2. B. power distribution network load demand (active and reactive) and water network load demand. There is often error in load prediction.

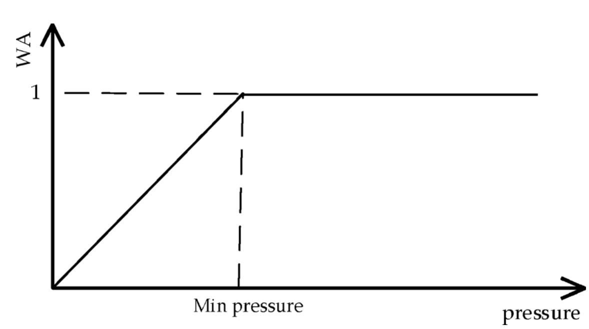

Fig. 2. Water pressure satisfaction function.

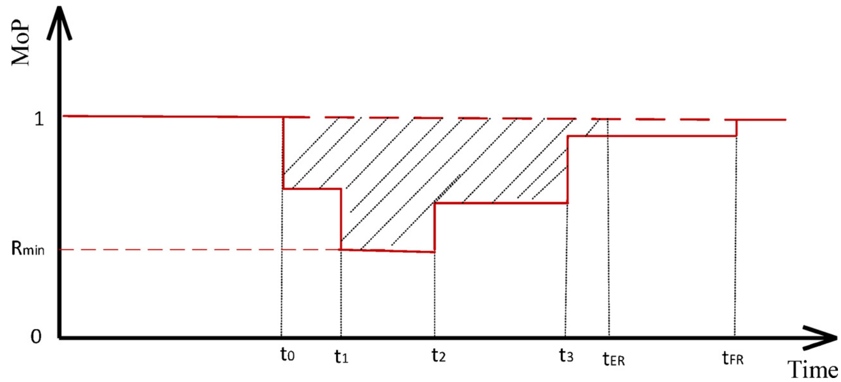

Fig. 3. Social welfare as measurement of performance of the network.

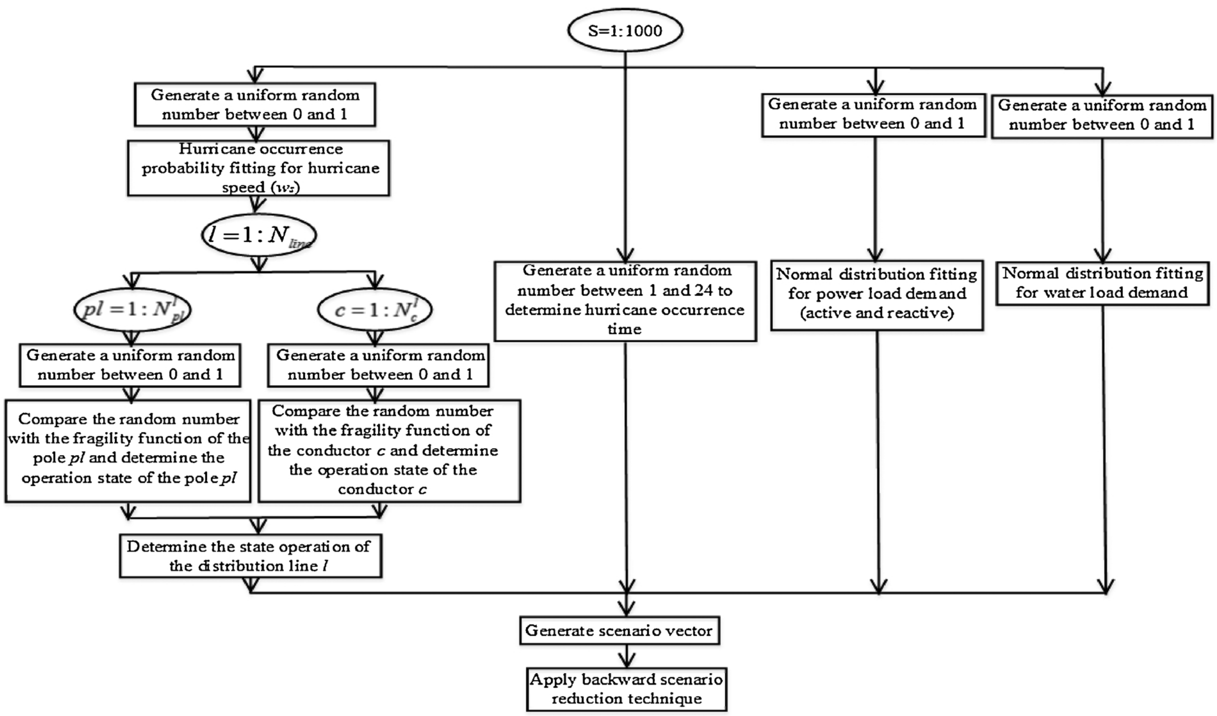

Fig. 4. Flowchart of scenario generation and reduction process.

This error should be considered in the studies. According to (Dolatabadi, Mohammadi-ivatloo, Abapour, & Tohidi, 2017), power distribution network load demand (active and reactive) prediction can be modeled using the normal of Gaussian PDF with 3% error. The uncertainty model of water network load demand is assumed similar to power network load demand.

2.3.1.3. C. Scenario reduction. In order to reduce the computational requirement to solve the stochastic problem, the backward reduction algorithm is utilized in this study for scenario reduction. It reduces the scenarios into a predefined number based on the Kantorovich distance (Growe-Kuska, Heitsch, & Romisch, 2003).

2.3.2. Mathematic formulation

In this section, the two-stage stochastic problem is formulated.

The objective function of the first stage is:

$$OF1 = \max_{X_l, X_i, cap_i^{DG}, N_{M\to R}} \sum_{s=1}^{S} \rho(s) RI(s) \tag{10}$$

In the planning problem, the budget is important. The budget constraint is according to (11):

$$\sum_{l=1}^{N_{line}} X_l C_l^H + \sum_{i=1}^{N_b} X_i C^{DG} cap_i^{DG} + N_{M\to R} C^{RS} \le B \tag{11}$$

In the second stage, each scenario is solved with the objective function in (12).

$$OF_2 = \max_{\substack{P_i^{m,s}, Q_i^{m,s}, |V_i^{m,s}|, \theta_{ij}^{m,s}, \left|I_{ij}^{m,s}\right|, \\ P_{loss,l}^{m,s}, Q_{loss,l}^{m,s}, P_{DGg}^{m,s}, Q_{DGg}^{m,s}}} MoP \tag{12}$$

A load is restored in a distribution system with the main network (which is supplied with a substation) or with an intentionally islanded formed microgrid with DG or DGs. The main network is restored with closing tie line switches and opening closed switches. Also, each DG or multi DGs can form a microgrid and restore the loads. In the main network and each intentional islanded microgrid, the constraints (13–16) must be satisfied in each scenario.

$$P_i^{m,s} = |V_i^{m,s}| \sum_{j\in BS_i} |V_j^{m,s}| (G_{ij}\cos\theta_{ij}^{m,s} + B_{ij}\sin\theta_{ij}^{m,s}), \quad s \in \{1,2,\ldots, S\},\ m \in \{1,2,\ldots M_s\},\ i \in \{1,2,\ldots N_b^{m,s}\} \tag{13}$$

$$Q_i^{m,s} = |V_i^{m,s}| \sum_{j \in BS_i} |V_j^{m,s}|(G_{ij}\sin\theta_{ij}^{m,s} - B_{ij}\cos\theta_{ij}^{m,s}), \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\}, i \in \{1,2,...N_b^{m,s}\} \tag{14}$$

$$|V_{\min}| \le |V_i^{m,s}| \le |V_{\max}|, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\}, i \in \{1,2,...N_b^{m,s}\} \tag{15}$$

$$|I_{ij}^{m,s}| \le |I_{ij}^{\max}|, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\}, i \in \{1,2,...N_b^{m,s}\}, j \in BS_i \tag{16}$$

The power balance constraints in (13–14) show that the power injection at bus i should be equal to the load demand at bus i. The line current and bus voltage limit are shown in (15) and (16).

$$N_b^{m,s} = N_{line}^{m,s} + 1, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\} \tag{17}$$

In addition to Eqs. (13)–(16), also for each scenario and for each intentional islanded microgrids, the Eqs. (18)–(23) must be satisfied.

$$\sum_{i=1}^{N_b^{m,s}} P_i^{m,s} + \sum_{l=1}^{N_{line}^{m,s}} P_{loss,l}^{m,s} \le \sum_{g=1}^{G^{m,s}} P_{DG_g}^{m,s}, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\} \tag{18}$$

$$\sum_{i=1}^{N_b^{m,s}} Q_i^{m,s} + \sum_{l=1}^{N_{line}^{m,s}} Q_{loss,l}^{m,s} \le \sum_{g=1}^{G^{m,s}} Q_{DG_g}^{m,s}, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\} \tag{19}$$

$$P_{DG_g}^{m,s} \le P_{DG_g}^{\max}, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\}, g \in \{1,2,..., G^{m,s}\} \tag{20}$$

$$Q_{DG_g}^{m,s} \le Q_{DG_g}^{\max}, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\}, g \in \{1,2,..., G^{m,s}\} \tag{21}$$

$$P_{DG_{g,i}}^{\max} \ge P_i^{m,s}, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\}, g \in \{1,2,..., G^{m,s}\} \tag{22}$$

$$Q_{DG_{g,i}}^{\max} \ge Q_i^{m,s}, \quad s \in \{1,2,..., S\}, m \in \{1,2,...M_s\}, g \in \{1,2,..., G^{m,s}\} \tag{23}$$

According to (18), the sum of the active power of the loads that will be picked up with microgrid m and the active power loss of distribution lines of the microgrid should not exceed the active power capacities of DG or DGs of the microgrid. This also should be satisfied for the reactive power as (19). According to (20–21), the active and reactive power of each DG should not exceed the maximum active and reactive capacity of that DG. The role of these DGs are backup generators. So, Eqs. (22)–(23) guarantee that in all conditions, the load of the bus on which the DG in placed is supplied with that DG.

3. Solution methodology

In this section, the procedures of solving the problem are illustrated in Fig. 5 and each part of Fig. 5 is explained individually.

3.1. Water network

For finding the water pressure of nodes in different states of water pumps, it is necessary to analyze the water network. EPANET software is used to model the water network. Then the pressure of all loads are obtained for water pumps states in all times of the day. The water network is designed similarly the power network which is studied in this paper. The approach is based on determining the position and kind of power load, estimating the population, and then calculating the amount of water consumption. Fig. 6 illustrates the designed water network. There are different elements such as nodes, water sources, tanks, water pipes and pumps in a water network. Real water networks may have a loop or branch or a combination of both topologies. In the designed water network, combinations of loop and branch topologies are implemented. Two pumps are located at nodes 33 and 5 in the water network that are electrically supplied from nodes 33 and 5 of the distribution system, respectively. Each node in the water network has a specified water consumption. The water network should be designed in such a way that several constraints such as mass conservation, energy conservation, flow velocity range and pressure head range are satisfied (Cunha and Sousa, 1999). The access of loads (nodes in water network) to water is proportional to water pressure head at the nodes. The minimum pressure head limit at the nodes of the water network should be 29 m. It is noticed that the load demand of water network is an uncertain set. So, the amount of water load demand in each scenario is different. This parameter should be adjusted in EPANET for each scenario analysis.

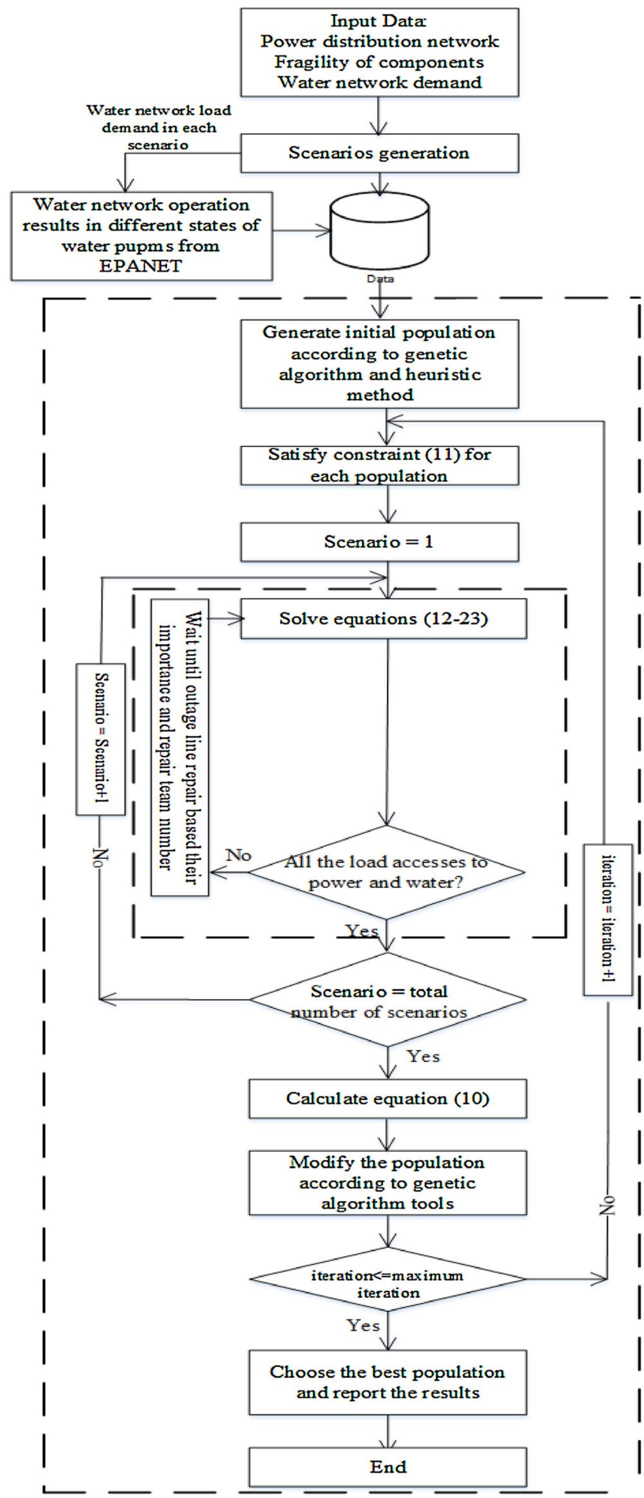

Fig. 5. Flowchart of solving the problem.

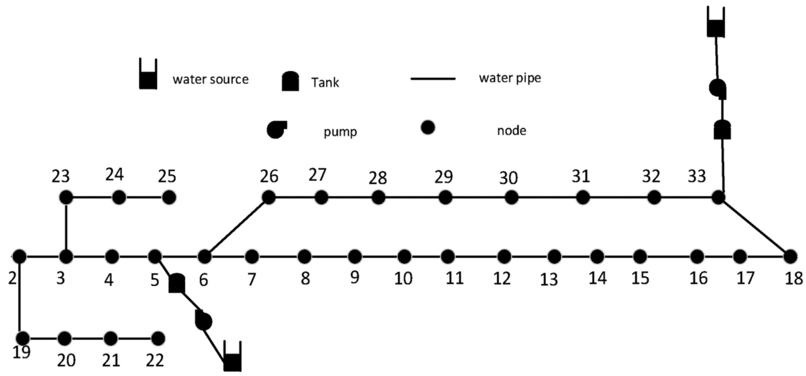

Fig. 6. The designed water network for IEEE 33-node distribution system.

The normal operation of water network is such that the water pressure of the nodes are in allowable limits. So, their water pressure satisfaction is 1. And when a water pump is stopped, the water pressure of some nodes will be decreased. And if all water pumps stop, the water pressure satisfaction of some nodes will be zero. In other words, the loads will not have access to water.

A water pump may be backed up is equipped with a generator such as diesel generator. Thus, first it is necessary to investigate that how long the generator can supply power for the water pump. For this period, the water pumps can work at times of power network failure.

3.2. How to solve the restoration problem

In this section, the second stage of the problem is explained. After fault clearance in the distribution system, the disconnected loads should be restored rapidly. Based on graph theory, we first determine if the distribution network is divided into islands and how many islands there are due to the faults (Jia and Xu, 2013; Peiravi and Ildarabadi, 2009). Then if it is possible, the main network (which is supplied by the substation) can be restored with tie line switches and the islanded networks can be restored by DGs. If we model the distribution network as a graph $Gr(N, E)$ where $N = \{1,2,\ldots, n\}$ is the set of vertices of the graph or nodes of the distribution network and E is the set of edges of the graph or lines of distribution network. The Laplacian matrix ($L(Gr)$) of the network is obtained according to (24).

$$L(Gr) = D(Gr) - A(Gr) \tag{24}$$

$A(Gr)$ is a symmetrical matrix which is calculated based on (25) and determines the state of each node with respect to other nodes. In other words, if there is an edge between two nodes, the state of these two nodes is one. Otherwise it is zero.

$$A(Gr) = \begin{pmatrix} a_{11} & \ldots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}, \quad a_{nn} = \begin{cases} 1 & e_{nn} \in E \\ 0 & e_{nn} \notin E \end{cases} \tag{25}$$

$D(Gr)$ or degree matrix is a diagonal matrix which is calculated based on (26).

$$D(Gr) = \begin{pmatrix} d_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & d_n \end{pmatrix}, \quad d_n = \sum_{i=1}^{n} a_{ni} \tag{26}$$

There is a relationship between eigenvalues of the Laplacian matrix and

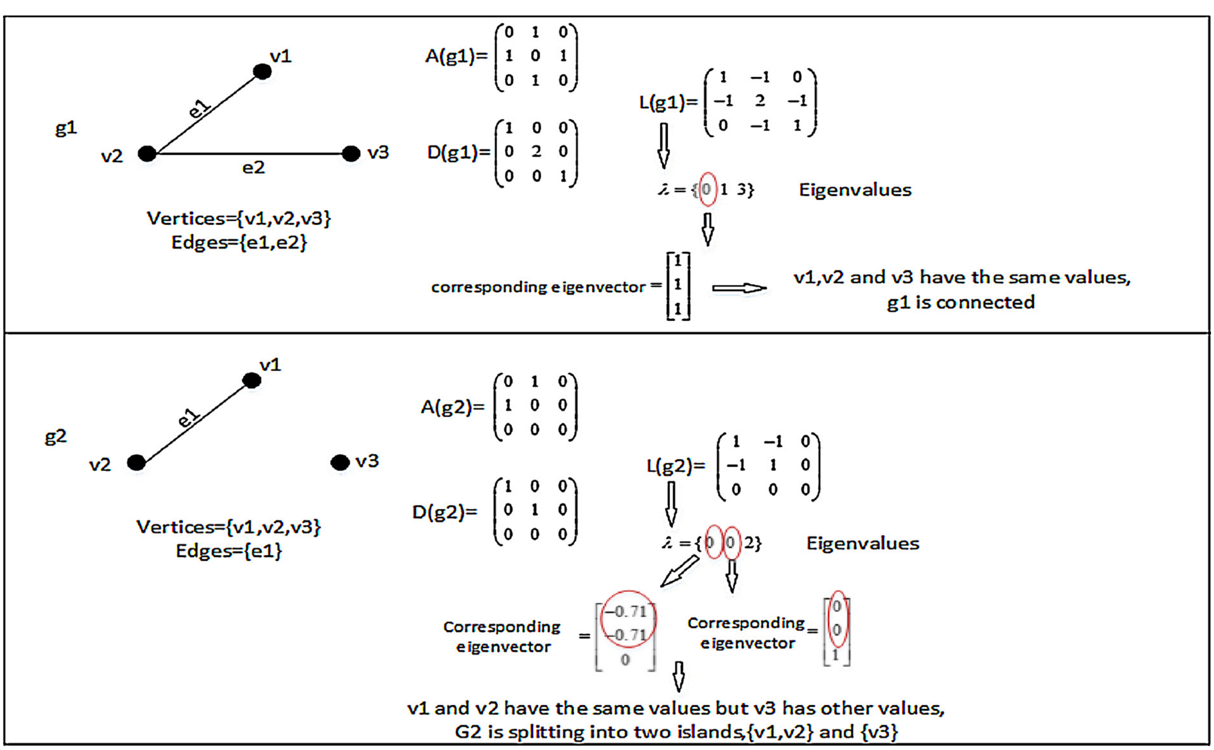

Fig. 7. The relationship between eigenvalues and graphs structure.

the structure of a graph. Fig. 7 illustrates two graphs g_1 and g_2. The vertices and edges of each graph are determined in Fig. 7. All matrixes (A, D and L) are calculated for each graph using (24–26). According to Perron-Frobenius theorem (Brown, 2009), for a connected graph such as g_1, only one eigenvalue of the Laplacian matrix is zero and the others are positive. The corresponding eigenvector of the zero eigenvalue is $[1 \ \ 1 \ \ 1]^T$. The number of zero eigenvalues of a separated graph such as g_2 determines the number of islands of the graph. According to Fig. 7, the components of each island can be determined by calculating the eigenvector of each zero eigenvalue. In other words, all of the vertices in an island have the same value in the eigenvectors.

There are two phases for restoration of the main network. In the first phase, as many tie lines switches as the number of outage lines in the main network should be closed. In the second phase, if a constraint is violated the reconfiguration of the network (closing another tie line switch and opening a closed line switch) is performed. If the constraints are not satisfied, a load should be disconnected and the two phases are performed again. The steps of the proposed approach for restoration of the main network are explained with an example. Considering Fig. 8, a single fault occurs in lines 4–5.

According to Fig. 8, there is one line outage in the main network. For the first phase, three switchings (21–8, 22–12 and 25–29) are candidates as assumed in this study. While according to (Yuan et al., 2017), there are $C_5^1 = 5$ candidates, for none of three switching. All the constraints are not satisfied, so it is necessary to perform phase 2. According to (Yuan et al., 2017), in each stage one tie line switch is closed. So, in the second step, all of the $C_5^2 = 10$ states of switching are candidates.

Voltage constraint is the tool that is used in this study to design the algorithm. In a radial distribution system, the voltage decreases from the nearest node to the supply to the farthest node to the supply. According to Fig. 9, only the tie line switches are candidates for the second phase and the bus voltage of one of the paths from the branches (g1 or g2) satisfies the voltage constraint and the others violate the voltage constraint.

Fig. 10 illustrates the results of the first phase and the minimum voltage of each branch paths of each switches. Four switching states are candidates for the second phase in which each state includes three switches. One switch is closed in the first stage and the remaining switches will be closed and opened in the second phase. If all the loads cannot be restored, the next step (in which three tie line switches should be closed) should be performed. For the next step, only the combination of R1, R2 or R3 possible switches are chosen. In other words, based on modified Viterbi algorithm ((Yuan et al., 2017)) for the next step there are $C_5^3 = 10$candidate states, while based on the proposed approach only one state (including 21–8, 25–29 and 18–33) is candidate.

So, with the proposed approach, with less candidate switching state checking compared to the modified Viterbi algorithm (Yuan et al., 2017), the time of solving the restoration will be decreased significantly. If again all the loads cannot be restored, the next step is not possible anymore based on the proposed approach, and load shedding should be performed. Loads are ranked based on two indices in order to choose the load to be shed. The first index is the voltage of the bus at which the load is located and the second index is the load importance. The load which is worse in the two indices than the other loads is chosen to be shed. The importance factor of each load except the loads which consist of water pumps is their power importance factor. However, for loads which consist of water pumps, their importance factors are the sum of their power importance factors and a time variable term includes water importance factor of other loads. The variable term depends on pump operation in the time interval in which the load will be disconnected. It is be noticed that if there is a DG in the main network, the DG is modeled as negative load.

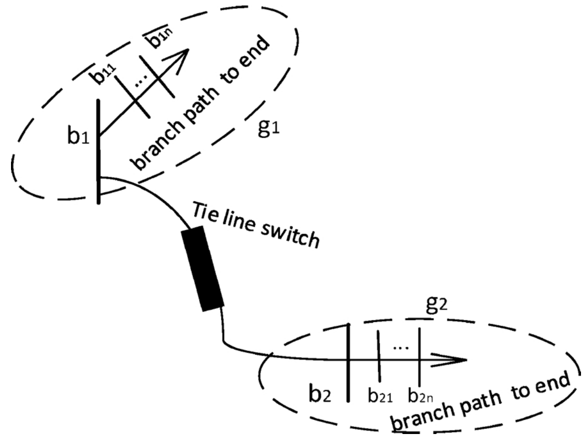

Fig. 9. A schematic of tie line switch.

If it is possible, the loads which are not in the main network should be restored by microgrid formation with DG or DGs. The stability of each microgrid is an important issue and the intentional microgrid should be equipped with droop or v-f control of DGs (Li et al., 2017). For each DG which is out of the main network, all of the states that can form a microgrid are produced. Then Eqs. (13)–(23) are considered for each state and the best state including a DG and several loads is chosen. If two or more DGs have a common restored load or there is a line between two buses of each microgrid, this means that those DGs and their islands can mix together and form a microgrid if load flow constraints are not ignored.

Depending on the number of distribution lines outage, it is possible that all of the loads cannot be restored. The outaged lines will be repaired with repair team units based on their importance and each line will go back to the network after repair. And again Eqs. (13)–(23) will be solved until all of the loads are restored. Each restoration plan has a specified time to operations. Depending on the number of switches which will be closed or opened, their control (manual or remote) and the number of loads will be disconnected and the number of crew is indicated. If the time between repairs of two lines is less than the restoration plan time, that restoration plan will not be performed. And the restoration plan will be performed which is obtained after the next line repair.

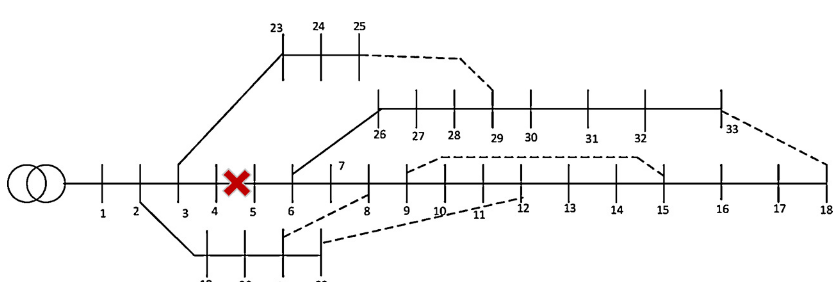

Fig. 8. 33-bus distribution system.

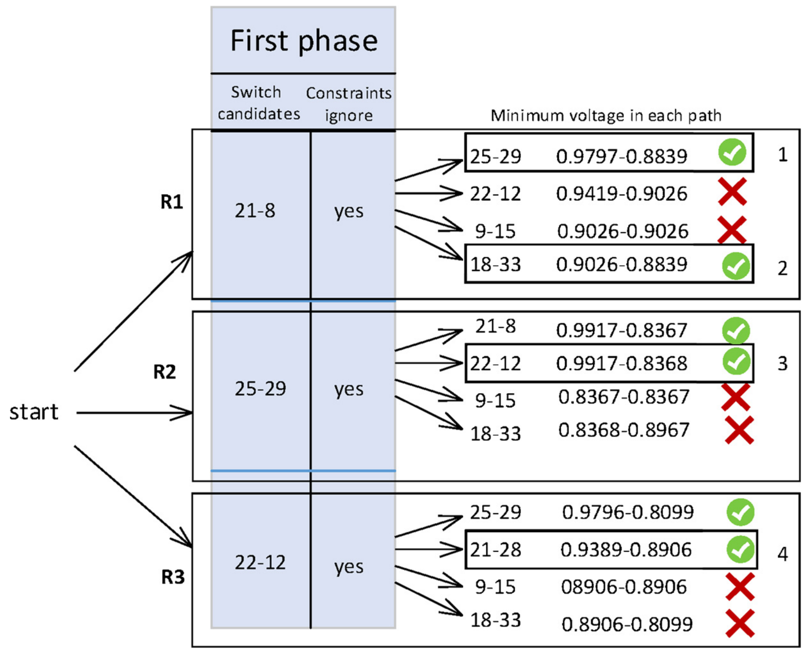

Fig. 10. The results of the first phase of example restoration.

3.3. How to solve the first stage of the problem

According to Fig. 5, genetic algorithm (GA) is applied to solve the first stage of the problem. The GA is an optimization method inspired by natural evolution (Goldeber, 1989). The designed chromosome (string) is shown in Fig. 11. According to Fig. 11, the first row of the chromosome includes gens as number as the distribution network lines which indicate the line is chosen to be harden or not. The second row of the chromosome includes gens as number as the distribution network buses which indicate the bus is chosen to be equipped with a DG with different capacities or not. The last row of the chromosome includes a gene for distribution network automation.

According to Maaranen, Miettinen, and Penttinen (2007), the initial population has an important role on the performance of GA. In order to generate the initial population, first, the impact of each strategy on resilience improvement is calculated with the scenarios. Thus, during initial population generation, each gene that its corresponding strategy has more impact on resilience improvement has a more chance for choosing. This heuristic method in initial population generation caused to the better performance of GA.

4. Results

In this section, computational experiments with the proposed model are performed. The program is implemented in the MATLAB R2010a software. All tests are performed on a PC with 3.4-GHz CPU and 32GB RAM. The IEEE 33-node distribution system with the designed water network shown in Fig. 5 are used to study the model.

The importance factor of each load (*LI*) is equal to the size of that load divided by the sum of all loads. In this paper, it is considered that for each load in the power system, there is a node in the water network. Loads 19–22 are commercial and others are domestic.

The information of IEEE 33-node distribution system is obtained from (Baran and Wu, 1989). The 24-h load multiplier of the distribution system and water network is illustrated in Fig. 12. The repair time for each pole and conductor is 6 and 4 h, respectively. There are four crew teams for opening and closing the manual switches and there are three repair teams or in other words three outaged lines can be repaired simultaneously. In this paper, it is assumed the require time for opening or closing of each manual controlled switches is one hour while this time for remote controlled switches is less than 1 min, so this time can be ignored in the study.

The cost of resilience improvement strategies are given in Table 1.

In solving the problem according to hurricane's historical date, fragility functions of lines and conductors, load demand of power distribution network water network, 50 scenarios are produced. The first state of the distribution system is without any strategies (no DGs are located in the network, no switches are equipped with remote-controlled and no lines are hardened).

4.1. Case a restoration of distribution system

In this section, the effectiveness of the proposed algorithm for restoration of the distribution system is investigated and is compared with a research study. The results are given in Table 2.

According to Table 2, the results show that the proposed method can restore the distribution system for different fault locations similar to (Yuan et al., 2017) but in less computation time as explained in Section 3.3. Most of the research works test the restoration program for single faults and a few of them such as (Yuan et al., 2017) test the program for multi faults.

In other case, considered that in a scenario, lines (7–8), (8–9), (12–13), (2–19), (30–31) and (18–33) are damaged due to hurricane. The repair time of line (12–13) is 12 h and that of the other lines is 6 h

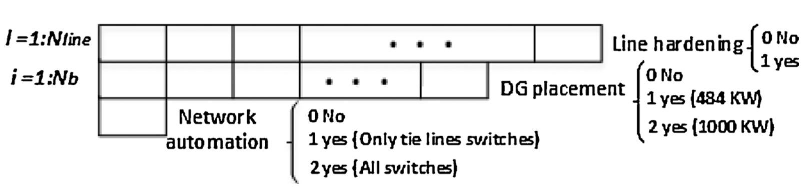

Fig. 11. The designed chromosome (string) for GA.

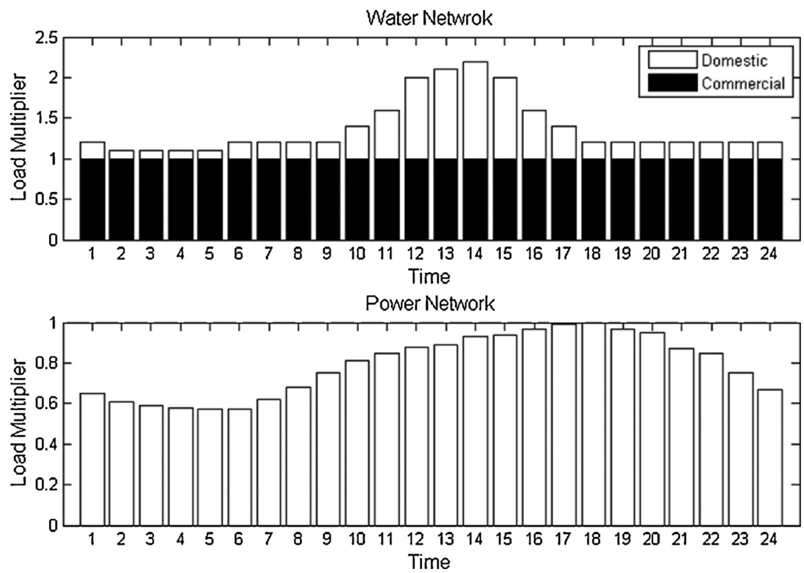

Fig. 12. Load multiplier of distribution system and water network.

Table 1
Cost of strategies to improve resilience.

Strategy	Cost ($)
Upgrading each pole	6000
484 KW DG placement	93000
1000 KW DG placement	194000
Tie lines switches automation	5 × 4700 = 23500
All lines switches automation	37 × 4700 = 173900

Table 2
The results of IEEE 33-node distribution system and comparison with other research studies.

	Proposed Method		Yuan et al. (2017)	
Fault location	Switching Operation	Load Restoration	Switching Operation	Load Restoration
4–5	Close (21-8), (25–29) Open (6–26)	100%	Close (12–22), (25–29) Open (6–26)	100%
11–12	Close (9–15)	100%	Close (12–22)	100%
4–5 & 27–28	Close (9–15), (25–29)	100%	Close (25–29), (8–21)	100%
4–5 & 11–12 & 27–28	Close (25–29), (21-8),(22-12)	100%	Close (9–15), (21-8),(25–29)	100%

and there are two repair teams in the network. The maximum time of repair for all outaged lines is 24 h.

The network is equipped with two DGs at nodes 8 and 11 with 400 and 200 MW capacities, respectively. The restoration of the network is solved and consider that this restoration plan is performed at 15 o'clock. According to Fig. 13, two networks including the main network and one islanded microgrid with DGs are formed. The loads of these networks are disconnected. The duration of performing the restoration plan depends on the switches that are remote-controlled or manual controlled. In this scenario, consider all of the switches to be controlled remotely. This restoration plan is in the network until the repair of the lines. It is assumed that there are two repair teams. Based on outage line importance, the two lines (7–8) and (30–31) will be repaired first by the repair teams. So, this restoration plan is until the two mentioned lines are repaired or it is in interval 15–21 o'clock. The water pump in node 33 stops to work due to outage of node 33 in the distribution system.

According to EPANET, between 15 o'clock and 16 o'clock due to water in tank in node 33 the pressure of the nodes are in normal state but between 16 o'clock and 21 o'clock, the water pressure of several nodes drops and water satisfaction function in those nodes decreases. Water accessibility function at 16 o'clock is depicted in Fig. 14.

At 21 o'clock, lines (7–8) and (30–31) are repaired and are ready for operation. The restoration problem is again solved for the remaining 18 h to maximize accesses of loads to power and water. The new restoration plan is depicted in Fig. 13. For changing the configuration of Figs. 13–15 it is necessary to close and open a few lines. With the new

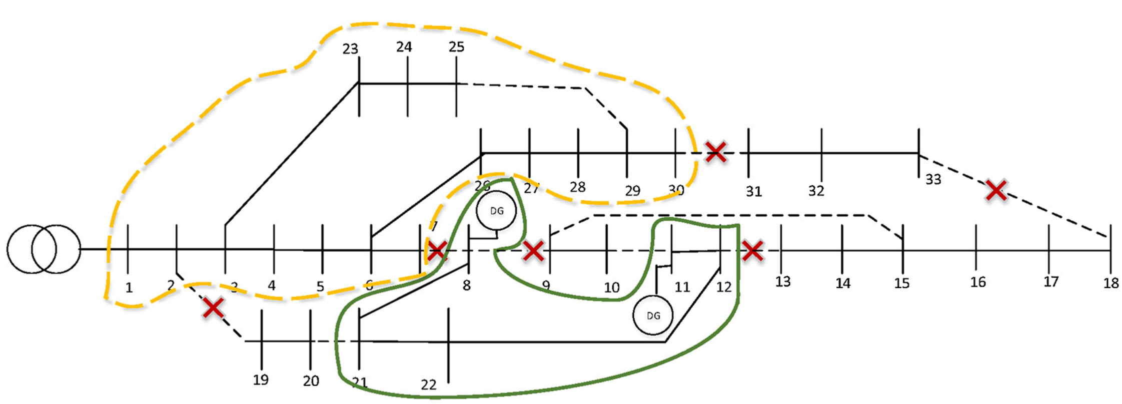

Fig. 13. Restoration plan in 15–21 o'clock.

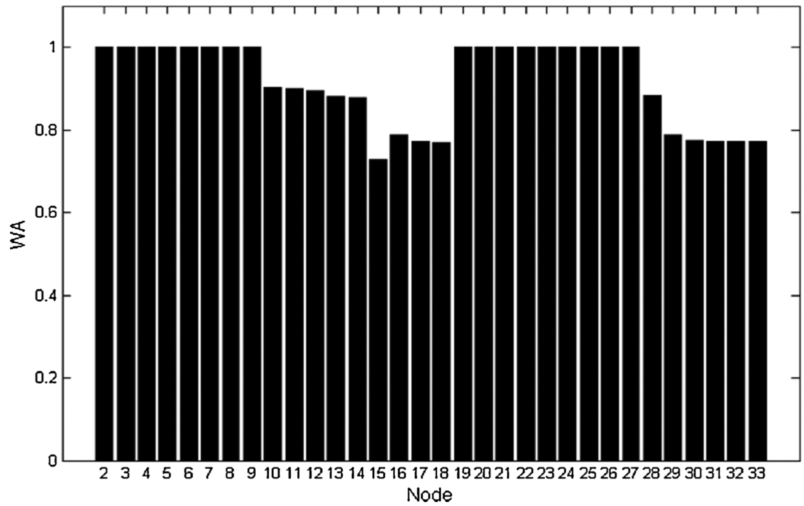

Fig. 14. Water satisfaction function at 15 o'clock when the pump in node 33 stops to work and the pump in node 5 works.

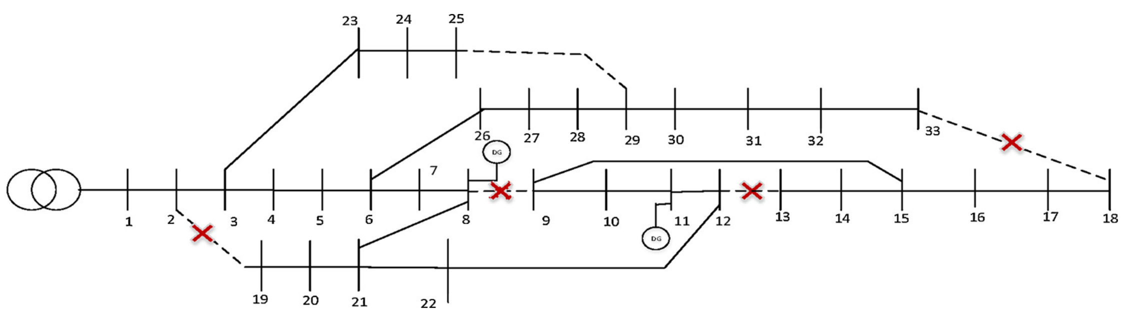

Fig. 15. Restoration plan in 21–3 o'clock.

Table 3
The results of distribution system resilience improvement against category 1 hurricanes.

B = 400000 $				
Line hardening		DG placement		Network automation
from	to	node	Capacity (kw)	
1	2	16	100	Upgrade tie line switches to
2	3	32	484	remote control switches
6	26			
RI without strategies: 2.464			*RI* with strategies: 2.863	

Table 4
The results of distribution system resilience improvement against category 4 hurricanes.

B = 500000 $				
Line hardening		DG placement		Network automation
from	to	node	Capacity (kw)	
1	2	5	484	Upgrade tie line switches to
2	3	33	484	remote control switches
2	19	25	1000	
6	19			
	26			
RI without strategies: 0.617			*RI* with strategies: 1.135	

restoration plan, all of the loads are restored and the water satisfaction function of all loads is 1. So, before all lines are repaired, the network can be restored completely and some loads experience outage for 6 h.

Table 5
The results of resilience planning.

B = 400000 $				
Line hardening		DG placement		Network automation
from	to	node	Capacity (kw)	
1	2	16	484	Upgrade tie line switches to
2	3	33	484	remote control switches
23	24			
25	29			
RI without strategies: 1.985			*RI* with strategies: 2.446	

4.2. Case B resilience distribution system planning for categories 1 and 4 hurricanes

In this case, distribution system resilience planning is solved for category 1 and 4 hurricanes with water network operation. To determine t_{ER} for calculatingSRI_2, 100 scenarios are produced for each hurricane category and the restoration problem is solved for each scenario of each category. Then the expected value of restoration time for each category is calculated for the scenarios by averaging the results. For categories 1–4, t_{ER} is 6, 8, 13 and 75 h, respectively. By considering the time of switching operation, t_{step} is assumed to be equal to 1 h.

The results of distribution system resilience improvement planning against category 1 and 4 of hurricane are shown in Table 3 and 4, respectively.

According to Table 3, one of the chosen strategies for resilience improvement of the network against category 1 hurricanes is upgrading the tie line manual switches to remote controlled switches to reduce restoration time. The number of faults due to first category hurricanes in the network are such that the network often will be restored with tie line switches. Two DG are chosen to be placed in the network which can form microgrids and restore the disconnected loads. Lines (1–2) and (2–3) are important lines that with outage one of them, all or most of the loads will be disconnected. Thus, both of them are chosen to be hardened. The last cheap strategy is line (6–26) hardening. It is noticed that budget constraint cause this cheap strategy be chosen. Otherwise, there are some more expensive and more efficient strategies.

In category 4, the faults due to natural disasters in the network are much more compared to category 1. According to Table 4, two DGs are chosen at nodes (5, 33) where the water pumps are located. Unlike category 1, in category 4 the water network dependency on power network is significant and has an important role in resilience planning. Due to high number of faults, another DG with 1000 KW is chosen at node 25 to back up two heavy loads 24 and 25. Similar to category 1, upgrading tie line switches and hardening lines (1–2), (2–3) and (6–26) are other important strategies that are chosen. Line (2–19) is the other strategy that is chosen to be harden. With this strategy, the reliability of loads (1–22) is increased against hurricane.

4.3. Case C distribution system planning to enhance resilience according to a determined hurricanes category occurrence probabilities

The probabilities of occurrence of a hurricane for each category are obtained from (Brown et al., 2006) and are 0.53, 0.19, 0.15 and 0.13. The result of the planning problem for enhancing the resilience of distribution system is illustrated in Table 5 that shows seven chosen strategies to enhance the resilience. The tie line switches are upgraded to remotely controlled switches. Although the probability of occurrence of higher storm categories is low, their failure severity is much more than that of the lower categories. Therefore, they have an important role in choosing strategies to improve resiliency. Only one of two nodes including water pump (node 33) is chosen to equip with a DG and with this strategy the dependency of the water network on the power network is reduced. Node 16 is also chosen to be equipped with a DG. The important lines (1–2), (2–3), (23–24) and (25–29) are chosen to be hardened. The results confirm that the severity of hurricanes in a region is an important parameter in the chosen resilience improvement strategy.

5. Conclusion

In this paper, the two stage stochastic distribution system planning problem is solved for enhancing resilience by using a new index based on social welfare. The new resilience index is used in an attempt to maximize the accessibility of loads to power and water in a minimum time after natural disasters. The water network is modeled with EPANET that calculates the node's water pressure in different operations of water pumps. The best strategies for increasing resilience were chosen with genetic algorithm according to the budget in the higher stage of the problem based on an index considering both resilience improvement and cost. In the lower stage of the problem, the restoration problem for each scenario is solved by maximizing social welfare until full restoration with a new proposed approach which is a modification of the method presented in (Yuan et al., 2017). The proposed approach can find the restoration plan with checking fewer switch states compared to (Yuan et al., 2017). The new proposed model for distribution system resilience planning is studied with two cases in this paper. In the first case, the mentioned problem is solved for category 1 and 4 hurricanes to find the best first four strategies to enhance resilience. Upgrading the tie line manual switches to remote controlled switches and hardening lines (1–2) and (2–3) are important strategies in each of the categories. Unlike category 1, in category 4, the dependency of water network on the power network is significant and the nodes including water pump equipped with DGs. The DG placement strategies has more impact in resilience improvement in category 4 of hurricane compared to category 1 of hurricane. In the other case, distribution system resilience planning was solved with determined hurricane categories considering the probability of occurrence. In this case, only one node including water pump is equipped with DG and a DG is place in other node. Other strategies include upgrading tie line switches to remote controlled switches and line hardening.

Microgrids as dependent networks can isolate themselves from the main network during and after natural disasters. In the future, we will study the interaction of microgrids with the distribution network to improve the resilience with the proposed index. An appropriate interaction can reduce the resilience improvement planning cos

References

Arab, A., Khodaei, A., Han, Z., & Khator, S. K. (2015a). Proactive recovery of electric power assets for resiliency enhancement. *IEEE Access, 3*, 99–109.

Arab, A., Khodaei, A., Khator, S. K., Ding, K., Emesih, V. A., & Han, Z. (2015b). Stochastic pre-hurricane restoration planning for electric power systems infrastructure. *IEEE Transactions Smart Grid, 6*(2), 1046–1054.

Arroyo, J. M., & Francisco, F. J. (2013). *A genetic algorithm for power system vulnerability analysis under multiple contingencies metaheuristics for Bi-level optimization.* Berlin Heidelberg: Springer41–68.

Baran, M. E., & Wu, F. F. (1989). Network reconfiguration in distribution systems for loss reduction and load balancing. *IEEE Transactions Power Delivery, 4*(2), 401–1407.

Bie, Z., Lin, Y., Li, G., & Li, F. (2017). Battling the extreme: a study on the power system resilience. *Proceedings of the IEEE, 105*(7), 1253–1266.

Bier, V. M., Gratz, E. R., Haphuriwat, N. J., Magua, W., & Wierzbicki, K. R. (2018). Methodology or identifying near-optimum interdiction strategies for a power transmission system. *Reliability Engineering & System Safety, 121*, 83–89.

Brown, G., Carlyle, M., Salmeron, J., & Wood, K. (2006). Defending critical infrastructure. *Interface, 36*(6), 530–544.

Brown, R. (2009). *Cost-Benefit Analysis of the Deployment of Utility Infrastructure Upgrades and Storm Hardening Programs, Quanta Tech., Raleigh, NC, Tech. Rep* (March, [Online]. Available:http://www.puc.texas.gov/industry/electric/reports/infra/utlityinfrastructure upgradesrpt.pdf.

Brown, R., Wang, X., & Page, C. (2016). *Are power utilities in Tonga and New Zealand resilient? human and organizational factors in disaster response.* Washington, D.C: World Bank.

Che, L., Khodayar, M., & Shahidehpour, M. (2014). Only connect: microgrids for distribution system restoration. *IEEE Power Energy Magazine, 12*(1), 70–81.

Chen, B. (2016). *Applications of optimization under uncertainty methods on power system planning problems, PhD. Dissertation.* Ames, Iowa: Dep. Ind. Eng., Iowa State Univ.

Chen, C., Wang, J., Qiu, F., & Zhao, D. (2015). Resilient distribution system by microgrids formation after natural disasters. *IEEE Transactions Smart Grid, 7*(2), 958–966.

Chen, C., Wang, J., & Ton, D. (2017). Modernizing distribution system restoration to achieve grid resiliency against extreme weather events: an integrated solution. *Proceedings of the IEEE, 105*(7), 1267–1288.

Cunha, M. C., & Sousa, J. (1999). Water distribution network design optimization: simulated annealing approach. *Water Resources Planning and Managing, 125*(4).

Dolatabadi, A., Mohammadi-ivatloo, B., Abapour, M., & Tohidi, S. (2017). Optimal stochastic design o wind integrated energy hub. *IEEE Transactions on Industrial Informatics, 13*(5), 2379–2388.

Espinoza, S., Panteli, M., Mancarella, P., & Rudnick, H. (2016). Multi-phase assessment and adaption of power systems resilience to natural hazards. *Electric Power System Research, 136*, 352–361.

Fotuhi-Firuzabad, M., Safdarian, A., Moeini-Aghtaie, M., Ghorani, R., Rastegar, M., & Farzin, H. (2016). Upcoming challenges of future electric power systems:sustainability and resiliency. *Scientia Iranica. Transaction A, Civil Engineering, 23*(4), 1565–1577.

Gao, H., Chen, Y., Xu, Y., & Liu, C.-C. (2016). Resilience-oriented critical load restoration using microgrids in distribution systems. *IEEE Transactions Smart Grid, 7*(6), 2837–2848.

Gholami, A., Aminifar, F., & Shahidehpour, M. (2016). Front lines against the darkness: enhancing the resilience of the electricity grid through microgrid facilities. *IEEE Electrification Magazine, 4*(1), 18–24.

Goldeber, D. E. (1989). *Genetic algorithm in search, optimization, and machine learning.* Addison-Wesley Publishing Company.

Growe-Kuska, N., Heitsch, H., & Romisch, W. (2003). Scenario reduction and scenario tree construction for power management problems. *Proc. IEEE PowerTech: vol. 3*.

Javanbakht, P., & Mohagheghi, S. (2014). A risk-averse security-constrained optimal power flow for a power grid subject to hurricanes. *Electric Power Systems Research, 116*, 408–418.

Jia, Y., & Xu, Z. (2013). A graph-algebraic approach for detecting islands in power system. *Innovative Smart Grid Technologies Europe (ISGT EUROPE) 2013 4th IEEE/PES*, 1–5.

Krishnamurthy, V., Kwasinski, A., & Dueñas-Osorio, L. (2016). Comparison of power and telecommunications dependencies and interdependencies in the 2011 Tohoku and 2010 Maule earthquakes. *Journal of Infrastructure Systems, 22*(3), 04016013.

Li, G., Zhang, P., Luh, P. B., Li, W., Bie, Z., Serna, C., & Zhao, Z. (2014). Risk analysis for distribution systems in the northeast U. S. under wind storms. *IEEE Transactions on Power Systems, 29*(2), 889–898.

Li, J., Ma, X. Y., Liu, C.-C., & Schneider, K. P. (2014). Distribution system restoration with microgrids using spanning tree search. *IEEE Transactions Power Syst. 29*(6), 3021–3029.

Li, Z., Shahidehpour, M., Aminifar, F., Alabdulwahab, A., & al-Turki, Y. (2017). Networked microgrids for enhancing the power system resilience. *Proceedings of the IEEE, 105*(7), 1289–1310.

Liu, X., Shahidehpour, M., Li, Z., Liu, X., Cao, Y., & Bie, Z. (2016). Microgrids for enhancement the power grid resilience in extreme conditions. *IEEE Transactions on Smart Grid, 8*(2), 589–597. http://dx.doi.org/10.1109/TSG.2016.2579999.

Ma, S., Chen, B., & Wang, Z. (2018). Resilience enhancement strategy for distribution system under extreme weather events. *IEEE Transactions Smart Grid, 9*(2), 1442–1451.

Maaranen, H., Miettinen, K., & Penttinen, A. (2007). On initial populations of a genetic algorithm for continuous optimization problems. *Journal of Global Optimization, 34*.

Ouyang, M., & Duenas-Osorio, L. (2014). Multi-dimensional hurricane resilience assessment of electric power systems. *Structural Safety, 48*, 15–24.

Panteli, C., Pickering, S., Wilkinson, R., & Dawson, P. (2017). Power system resilience to extreme weather: fragility modelling, probabilistic impact assessment, and adaptation measures. *IEEE Transactions on Power Systems, 32*(5), 3747–3757.

Panteli, M., & Mancarella, P. (2015). Modelling and evaluating the resilience of critical electrical power infrastructure to extreme weather events. *IEEE System Journal,* 1–10.

Peiravi, A., & Ildarabadi, R. (2009). Complexities of using graph partitioning in modern scientific problems and application to power system islanding. *Journal of American Science, 5*(5), 1–12.

President's Council of Economic Advisers and the U.S. Department of Energy's Office of Electricity and Energy Reliability (2013). *Economic benefits of increasing electric grid resilience to weather outages.* Washington, DC, USA: Executive Office of the President, U.S. Dept. Energy (Tech. Rep., August).

Saffir-Simpson Hurricane Wind Scale (2017). *Nhc.noaa.gov.* [Online], Available:http://www.nhc.noaa.gov/aboutsshws.php (Accesse 18 June 2017).

T. N. A. of sciences (2012). *Disaster resilience: a national imperative.* Washington, DC: The National Academies Press.

Tran, H. T., Balchanos, M., Domercant, J. C., & Mavris, D. N. (2017). A framework for the quantitative assessment of performance-based system resilience. *Journal of Reliability & Safety, 158*, 73–84.

Wang, F., Chen, C., Li, C., Cao, Y., Li, Y., & Zhou, B. (2017). A multi-stage restoration method for medium-voltage distribution system with DGs. *EEE Transactions Smart Grid, 8*(6), 2627–2636.

Xu, Y., Liu, C. C., Schnieder, K. P., Tuffner, F. K., & Ton, T. (2018). Microgrids for service restoration to critical load in a resilient distribution system. *IEEE Transactions Smart Grid, 9*(1), 426–437.

Yuan, C., Illindala, M. S., & Khalsa, A. S. (2017). Modified Viterbi algorithm based distribution system strategy for grid resiliency. *IEEE Transactions Power Delivery, 32*(1), 310–319.

Yuan, W., Wang, J., Qiu, F., Chen, C., Kang, C., & Zeng, B. (2016). Robust optimization-based resilient distribution network planning against natural disasters. *IEEE Transactions Smart Grid, 7*(6), 2817–2826.

Yuan, W., Zhao, L., & Zeng, B. (2007). Optimal power grid protection through a defender attacker–defender model. *Reliability Engineering & System Safety, 92*(9), 1155–1161.

Zhang, Y., Yang, N., & Lall, U. (2016). Modeling and simulation of the vulnerability of interdependent power-water infrastructure networks to cascading failures. *Journal of Systems Science and Systems Engineering, 25*(1), 102–118.