Electric Power Systems Research 165 (2018) 1–8

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Pre-hurricane optimal placement model of repair teams to improve distribution network resilience

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ARTICLE INFO

Keywords:
Emergency response
Fragility curve
Hurricane
Monte Carlo simulation
Resilience
Square grid topology

ABSTRACT

Predictive planning for restoration and emergency reaction before occurrence of hurricane is an effective action in reducing time and cost of electricity interruption and improving resilience in overhead distribution networks. Traditionally, approaches in load and system recovery are constructed based on reliability studies, with the consideration of equipment failure. However, widespread outages due to the extreme natural events with low probability and high destruction intensity have different properties in comparing the interruptions due to the failures in equipment. Therefore, this paper proposes a new method for restoration and emergency reaction planning. The purpose of this method is resilience improvement of distribution network against hurricane. In the proposed pre-hurricane repair team placement model (PHRTPM), using Monte Carlo simulation method and fragility curves, different failure samples of poles and conductors of medium voltage distribution network are generated according to the predicted speed of hurricane. Furthermore, the forward dynamic programming algorithm is used to determine the path of the repair teams. In this method, using a square grid topology, the optimum locations of utility teams are achieved. The objective function of problem considers the importance of loads and the cost of outages. In the numerical studies, the proposed model is implemented on a modified and real distribution network in Iran which consisted of 81 buses. The results are discussed and the sensitivity analysis is performed for various parameters.

1. Introduction

Various natural hazards, such as hurricanes and wind storms, can threaten the resilience of power distribution networks. Natural catastrophes, which can occur in different geographical areas in different times, can create undesirable social, technical, economic and organizational consequential problems by causing outages and widespread blackouts. Due to global warming and climate change, natural disasters have occurred with much intensity during the past few decades. Furthermore, it is expected that the number, severity, and time period of these events will be increased in the future [1]. Nowadays, considering the mentioned issues, and given the extreme dependence of critical infrastructures on electrical energy (including transportation, economic activities, health system, purification and supply of drinking water, and emergency services), strengthening of energy infrastructure and increasing its resilience have become necessary as an important priority [2]. Although authentic standards exist for power system reliability, there is no comprehensive standard or guideline in the domain of power system resilience studies.

In Ref. [3], the UK Energy Research Centre (UKERC), stated a new definition of resilience: “Resilience is the capacity or the ability of a system to withstand disturbances and the capability of delivering continuous energy to consumers.” A resilient energy system can quickly recover from shock mode and can offer alternatives for energy requirements in the advent of incidents resulting from an external event. In the National Infrastructure Advisory Council (NIAC) definition, strength, resource adequacy, fast recovery, and adaptability are introduced as the main features of resilience [4]. In the mentioned definitions, quick restoration of curtailed loads is considered as one of the main features of resilience.

In the context of the system resiliency and emergency response, two study areas exist including: (i) Assessment and forecasting of outage rate and damage level and (ii) Recovery and resource allocation.

The first domain, the assessment and forecasting of outage rate and damage level caused by the occurrence of destructive events such as hurricanes, is considered in some literature. Ref. [5] analyzes the mutual effects between biophysical environment and power distribution networks from resilience viewpoint and offers prioritizing method for recovery activities of this environment. Moreover, Ref. [6] provides a statistical method based on data fitting using a large database of past

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https://doi.org/10.1016/j.epsr.2018.08.016
Received 1 January 2018; Received in revised form 18 August 2018; Accepted 21 August 2018

storms that predicts the restoration time of power networks. The proposed model improves the notification process to consumers for required time to restore the damaged networks after the storm. In Ref. [7], a data mining approach is proposed to assess the impact of climate and geographical conditions on blackout predicting models related to the storm event. In Ref. [8], a probabilistic framework is studied for vulnerability analysis of distribution network poles with respect to climate change. From the results, the life of poles and climate changes affect the failure rates of distribution network poles. In Ref. [9], the concept of resilience trapezoid is developed to assess the different time phases of resilience which a power system can experience during a severe event. This approach provides an effective aid to understand the features related to performance degradation and system recovery process by using time dependent indicators. In addition, operational and structural resilience and the strategies to improve them are presented in this paper. In Ref. [10], a supporting tool is described, with the aim of improving the supervision on the situation, promotion of accessing to information for distribution companies, and recovery management of damaged equipment due to severe storms. In this reference, the site of switching and protection equipment and the location of the consumers are determined in order to allocate resources based on a cost/benefit pattern for blackouts caused by the storm.

The occurrence of a natural disaster can damage the infrastructure of power system consequently leading to power interruption. After this event, the most important task of the system operator is power system recovery in the shortest possible time, with the aim of restoring the sensitive loads and reducing economic damages imposed to the consumers [11].

In the second context, i.e. recovery and resource allocation, preventive planning for real time emergency response (for instance locating and determining the number of repair teams) is one of the most important fields in resilience studies of power systems which has been investigated by different researches. In line with this topic, Ref. [12] provides a non-deterministic and two-stage preventive model for retrieving and allocating resources before the occurrence of storm. Ref. [13] presents three mathematical models for allocating the locations of repair teams and restoration of distribution and transmission lines. Optimal tactical plan of repair teams in extreme weather conditions, short-term strategic plan for optimal placing of repair teams in normal weather conditions, and determining the optimal number of teams for long term planning are the proposed models of this paper. In Ref. [14], a decision making problem for load restoration in densely populated areas is proposed which maximizes the retrieved power in the post-disaster recovery process. The problem is modeled by a mixed-integer programming. In Ref. [15], the warehouses siting model with the objective of optimal restoration is developed to manage the resource and crew needs with economic considerations. The purposes of this paper include determining the appropriate number of warehouses, the optimum warehouse locations, and the optimum number of repair teams including repair vehicles, crews, and equipment. In Ref. [16], load restoration problem is studied to minimize the service interruption considering the constraints of transportation in the emergency conditions. In this problem the issue of restoration resources is considered in a systematic way to obtain the optimal time of service actions. Ref. [17] provides a non-deterministic integer programming method developed for planning, damage evaluation, and scheduling of repair for restoration of power systems after an earthquake. The optimization problem, which minimizes the service interruption time, is solved using the genetic algorithm. In Ref. [18], to assess the extent of the failure, destruction and restoration of power systems after natural disasters, an approach is presented. Ref. [19] provides an analytical statistical model that utilizes data of interruptions in power grids during storm. This model, with the utilizing of publicly available information and data, could predict the interruption in electricity along US coastline and provides an approach for decision makers to determine the appropriate location and geographical distribution of resources. Ref. [20] proposes a multi-objective optimization technique for system restoration during disaster recovery. This model permits tradeoffs between cost minimization and system power flow maximization. Furthermore, Ref. [21] studies the proactive recovery strategies to retrieve power system assets.

As demonstrated by the literature review, there are only few works in the scope of resiliency and emergency response against hurricane hazard in distribution network. Hence, in this paper, a pre-hurricane repair team placement model (PHRTPM) is proposed as a heuristic model that aims to find the best locations of the operational crews and vehicles to improve the resilience of the network prior to the storm occurrence. Using this model, the best locations and number of repair teams can be obtained according to the costs. This approach is a good basis for distribution companies to make decisions according to their resources before the storm. In order to take into account the uncertainty of network equipment damage against a predicted storm, probabilistic investigations of the storm destruction are conducted based on the Monte Carlo simulation (MCS). In the presented model, with the intention of deciding the path through which the restoration team moves toward the destructed regions, a heuristic technique based on a square grid topology and forward dynamic programming algorithm is used. The proposed model of this paper has been applied to a real modified distribution network in Iran. Considering the literature review, the main advantages of the proposed model are: (1) a heuristic technique based on a square grid topology is proposed which is applicable for large real systems, (2) the proposed objective function considers the lost profits and penalty factor cost of distribution company simultaneously, (3) the probabilistic nature of destructive events and the uncertainty of equipment failure are considered, (4) the proposed model do not need wide information and data base, (5) it presents a pre-storm proactive restoration planning. Therefore, it can help DSO for pre-disaster preparation, (6) the proposed approach can be generalized for other natural disasters like thunderstorms, ice storms and floods because it is not dependent to the procedure of obtaining fragility curves of components.

The second part of the paper presents the proposed model. In this section, the suggested algorithms of the heuristic method are described. The simulation results are described in Section 3, and the discussions are presented. Finally, the conclusions are provided in the last section.

2. Proposed PHRTPM

Occurrence of storm causes damage to the poles and network conductors. Under such circumstances, it is necessary that crews arrive to more important sites in the shortest possible time, with aim of commencing restoration operations. At the same time, decision-making on the basic recovery indicators is of high importance. The main goal of PHRTPM is to find the best places for units of restoration resources before the storm and to calculate the decision indicators. According to Fig. 1, this method fulfills these goals based on the weather forecasting information and the distribution system data using some computations.

2.1. Description of the proposed model

In the proposed model, by having prior knowledge of the number of crews and vehicles (cr) and the candidate positions (cp), a large number of failure samples of poles and network conductors are generated based on the Monte Carlo sampling method. For each failure sampling, with a consideration of different permutations of distinct repair teams in the selected candidate locations (the number of permutations is cp^{cr}), the routing is determined from the viewpoint of minimizing the objective function using the forward dynamic programming algorithm. In each iteration of MCS, three permutations with the lowest values of objective function are selected and weighted from 3 to 1. When the MCS is completed, all the allocated weights are gathered for each permutation. Finally, among all the permutations (having a permutation number as