Applied Energy 162 (2016) 1571–1578

Contents lists available at ScienceDirect

Applied Energy

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

Customer satisfaction based reliability evaluation of active distribution networks ☆

Gengfeng Li, Zhaohong Bie *, Haipeng Xie, Yanling Lin

State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- Established operation optimization model of ADNs.
- Combined operation optimization processes and reliability evaluation of ADNs.
- Implemented reliability evaluation of ADNs considering customer satisfaction.
- Defined customer satisfaction originated reliability indices of ADNs.

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form 1 February 2015
Accepted 26 February 2015
Available online 1 April 2015

Keywords:
Reliability evaluation
Active distribution networks
Customer satisfaction
Sequential Monte Carlo simulation

ABSTRACT

Reliability evaluation of active distribution networks (ADNs) considering customer satisfaction is studied in this paper. Operation optimization model of ADNs is established, which aims to maximize the operation benefit of ADNs using demand response. However, according to optimization decisions, customers may have to change their electricity consumption habit, which affects customer satisfaction and the reliability of customers and ADNs. Two customer satisfaction indices are defined therefore as constraints in the operation optimization to quantify these effects. By a Sequential Monte Carlo (SMC) simulation, the optimization processes is innovatively integrated into the reliability evaluation, and thus the impacts of customer satisfaction constraints are incorporated in reliability evaluation. Further, four new reliability indices are defined in this paper to visibly reflect their impacts. The presented models and methods are validated by extensive studies conducted on a standard test system. Evaluation results accurately quantify the impacts of customer satisfaction constraints on load profiles, reliability and economic performance of ADNs. Conclusions drawn from evaluation results can provide helpful insights for distribution system operators (DSOs) to effectively improve the reliability and operation economy of ADNs using demand resources.

1. Introduction

Renewable energy (RE) resources (such as wind and solar) have drawn attention from researchers in the world because of their environmentally-friendly features [1]. Renewable energy generation is a major way of exploiting RE resources [2–4]. However, due to their intermittency and uncertainty, it is challenging to integrate RE resources into electrical distribution networks [5]. Active distribution networks (ADNs), which can properly and actively control the combination of distributed energy resources (DERs, including RE generators, controllable loads and storages), are emerging paradigms for effective utilization of RE resources [6].

Researches of ADNs have been focused on the theories and technologies of ADN measurement, protection and control, and a series of achievements have been published [7–12]. Ref. [7] described the performances of a phasor measurement unit (PMU) prototype based on a synchrophasor estimation algorithm conceived for the monitoring of active distribution networks, as well as its experimental application during some intentional islanding and reconnection tests of an urban medium voltage power network. Ref. [8] proposed a protection scheme on the basis of measured impedance, which included an impedance differential method and an inverse-time low-impedance method. Refs. [9–12] investigated the mechanism, models, and approaches of ADN control. Besides,

☆ This article is based on a short proceedings paper in Energy Procedia Volume 161 (2014). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal. This paper is included in the Special Issue of ICAE2014 edited by Prof. J Yan, Prof. DJ Lee, Prof. SK Chou, and Prof. U Desideri.

* Corresponding author. Tel.: +86 29 8266 8655; fax: +86 29 8266 5489.
E-mail address: zhbie@mail.xjtu.edu.cn (Z. Bie).

http://dx.doi.org/10.1016/j.apenergy.2015.02.084
0306-2619/

researches on ADN planning also receive increasing attention recently [13–17]. As an integral part of system planning, researches on the reliability evaluation of ADNs is significant, but few literatures have been focused on this topic.

In ADNs, interruptible loads, controllable loads, and energy storage devices are demand resources that can mitigate the intermittency of RE resources and reduce system operation cost [18,19]. Ref. [19], studied how demand response can contribute to the better integration of renewable energy resources such as wind power, solar, small hydro, biomass and combined heat and power (CHP). The latest distribution management systems tend to utilize optimization algorithm for the short-term scheduling of the various energy resource outputs and these demand resources available in the network [20]. In other words, distribution system operators (DSOs) can optimize day-ahead operation schedules based on electricity price signal and/or direct load control. In Ref. [20], a short-term scheduling procedure for ADNs was adopted, which was composed by two stages: a day-ahead schedule for the optimization of distributed resources production during the following day; an intra-day schedule that for every 15 min reschedule based on the updated operation requirements and constraints of the distribution network. Ref. [21] proposed an optimal operational scheduling framework to be used in the distribution management system (DMS) as the core of smart active distribution networks. Operational scheduling and demand-side management (namely operation optimization) indicate that customers have to change their electricity consumption habits, but whether customers are satisfied with these changes, and to what extent they are willing to change are significant factors. They will affect customers' response strategies and determine the effects of the operation optimization on reliability performance. However, few literatures have addressed this topic. To appropriately model customer satisfaction in operation optimization models, and incorporate its effects in ADN reliability evaluation are waiting to be investigated.

This paper establishes a new model for the operation optimization of ADNs, and the optimization processes are innovatively integrated into the reliability evaluation procedures by a Sequential Monte Carlo (SMC) simulation. To study the effects of customer satisfaction on ADNs reliability, two customer satisfaction indices (electricity consumption based and electricity cost based) are defined respectively, and adopted as constraints in the operation optimization model. Besides, four new reliability indices are defined to quantify the impacts of these constraints on the reliability of ADNs. Extensive studies are conducted on a standard test system to validate the presented models and methods. Evaluation results accurately quantify the impacts of customer satisfaction on load profiles, reliability and economic performance of ADNs. Conclusions drawn from the results are insightful for improving ADNs' reliability and operation economy using demand resources.

The organization of this paper is as follows. Section 2 describes the operation optimization model considering customer satisfaction. Section 3 presents a reliability evaluation framework for ADNs, in which the operation optimization is integrated into reliability evaluation. Test cases and result analysis are summarized in Section 4, followed by Section 5 that concludes the paper.

2. Operation optimization considering customer satisfaction

Because of the integration of distributed generation, controllable load, demand response, etc., ADN becomes in essence different from traditional distribution network. This section will first give the basic structure of ADN and its typical operation mode, and then build its operation optimization model. Customer response in the operation optimization will be discussed, and corresponding customer satisfaction indices will be defined and introduced into the optimization model.

2.1. Structure and operation modes of active distribution networks

One obvious distinction between ADN and traditional distribution network is that ADN can actively control DG, storage devices and controllable load through the operation center and communication technology (see Fig. 1). The implementation of the active management in an ADN can be briefly summarized as follows: (1) renewable energy generation are estimated using their probability models based on weather forecast information [22]; (2) operation center optimizes response strategies to follow renewable energy generation and to maximize ADN's operation benefit; (3) control commands are sent out to control the loads, generators, and energy storage devices. The core of this active management is the operation optimization, which will be introduced as follows.

2.2. Operation optimization models

The operation optimization model of ADNs was established based on the operation features of renewable energy generators, traditional distributed generators (such as diesel generators), response loads (controllable loads and interruptible loads), and energy storage devices. The optimization model includes an objective function and several constraints, which will be introduced as follows.

(1) Objective function of the operation optimization

The objective of operation optimization is to maximize the operational economic benefit of ADNs, and the objective function can be described as follows:

$$\max \cdot C = B_{load} - (C_{es} + C_{gen} + C_{grid}), \tag{1}$$

where B_{load} is the benefit of customers obtained from electricity consumption or compensation, and can be described as follows:

$$B_{load} = \sum_{t=1}^{T} (B_{vip} P^t_{vip} + B_{con} P^t_{con} + B^t_{cut}) \Delta t, \tag{2}$$

where P^t_{vip} and P^t_{con} are the power consumption of critical loads and controllable loads, respectively. The benefit coefficients of critical loads and controllable loads are B_{vip}, and B_{con}, respectively.

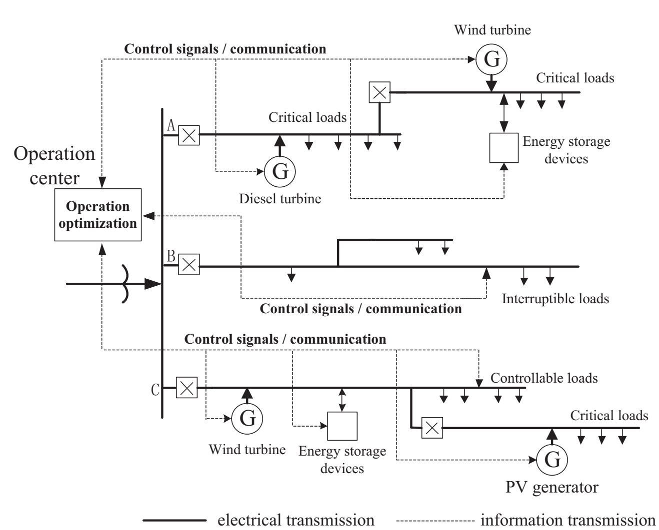

Fig. 1. The structure and operation modes of active distribution networks.