An Analytical Approach for Reliability Evaluation of Distribution Systems Containing Dispatchable and Nondispatchable Renewable DG Units

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***Abstract*—With ever increasing penetration of renewable distributed generation (DG) in distribution systems, power restoration of remote distribution feeders under emergency conditions tends to be carried out with the support of renewable DG units. The available power from the renewable DG units ensures restoration of more number of affected customers, thus, improving overall system reliability. In this paper, a probabilistic based analytical method is developed to assess system reliability in terms of system average interruption duration index and system average interruption frequency index for distribution feeders containing dispatchable and nondispatchable renewable DG units. The proposed method has been developed by implementing DG side restoration with comprehensive technical considerations, including possible failures of DG units, time-dependent patterns of load demand and DG power output, and single-stage and two-stage restoration. The proposed analytical method is validated by comparing with the Monte Carlo simulation and results are presented.**

***Index Terms*—Distributed generation (DG), distribution system reliability, load restoration, solar power, wind power.**

I. Introduction

RENEWABLE distributed generation (DG) units, such as biomass, wind, and solar energy, have been increasingly getting interconnected in remote or rural distribution systems, due to their positive impacts on the network. The integration of dispatchable renewable DG units such as biomass, biogas, and biodiesel based generators in remote distribution networks has been seen as one of the cost-effective options, for meeting increasing load demand, while maintaining overall system reliability. In recent years, the nondispatchable renewable DG units, such as wind and solar based generating systems, have been widely deployed into distribution systems in the wake of environmental concerns and associated incentives. The nondispatchable renewable DG units may bring additional reliability benefits to the system, as they can be operated along with the dispatchable renewable DG units, thereby minimizing customer interruptions, in case of system emergencies.

The system reliability for DG enhanced distribution networks can be assessed, by using random sampling based computational methods and analytical techniques. In [1], a time-sequential simulation method is presented to evaluate reliability cost for a distribution system containing wind turbine generators (WTGs). In [2], a set of reliability indices has been proposed, so as to directly quantify the system reliability benefits of adding WTGs in a rural distribution feeder. The optimal operational strategy of conventional DG units has been proposed in [3], with the consideration of hourly reliability worth, which is related to the operational modes of the DG units. In [4] and [5], the impacts of DG placement on system performance in terms of power loss and reliability are investigated with the consideration of time-dependent loading patterns. Chowdhury *et al.* [6] have analyzed the system reliability for distribution systems with conventional DG units (such as diesel generators and gas turbines), by considering the system planning perspectives. A methodology for evaluating the probabilistic reliability considering demand side management and web based online daily time interval reliability integrated information system is proposed in [7], for a grid constrained composite power system with WTGs. A novel approach based on minimal cut-sets and chronological Monte Carlo simulation has been proposed in [8], to assess the impact of grid integrated DG resources on the reliability indices. Reliability and economic indices of a microgrid equipped with high reliability distribution system switches, implemented at the Illinois Institute of Technology, USA, are analyzed in [9]. In [10] and [11], analytical methods are proposed for reliability assessment of multiple DG enhanced distribution system and microgrid, respectively, while accounting DG operational modes, restoration order of DG units, and load duration curve. In [12], the reliability of a distribution system with the inclusion of WTGs is estimated using a wind speed prediction technique. Moreover, a probabilistic correlation between output of WTGs and load profile during the islanded mode of operation is also considered in the paper. In [13], an analytical approach has been proposed, to evaluate distribution system reliability with specific consideration of DG modeling. The analytical methods discussed above have assumed minimal

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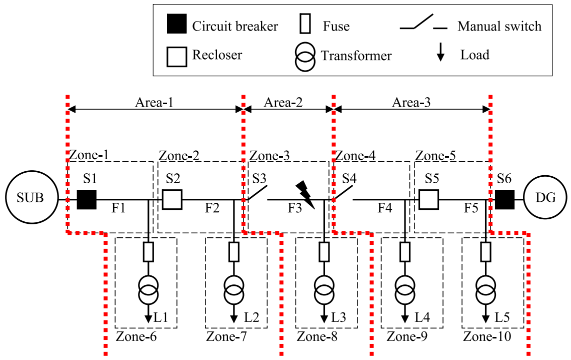

Fig. 1. Sample DG enhanced distribution feeder.

mismatch between load demand and DG power output, during the restoration period, for evaluating the reliability of DG enhanced networks. This assumption could be valid for the reliability assessment of distribution feeders with dispatchable DG units and insignificant variation of load demand during restoration. However, it may not be applicable to the distribution feeders, where the load demand and DG power output constantly vary in the restoration period. Therefore, a new methodology needs to be developed for reliability assessment of distribution systems with renewable DG units.

In this paper, a probabilistic based analytical method is proposed, to account for the time-dependent patterns of load demand and DG power output, leading to demand-generation mismatch, during restoration period under emergency system conditions. Thus, the main contribution of this paper is the development of probabilistic method for accessing customer side reliability for a power distribution system embedded with dispatchable and nondispatchable renewable DG units. The effectiveness of proposed method has been justified by conducting comparative studies.

This paper is organized as follows. Section II presents an analytical formulation for the evaluation of system reliability. Section III describes the proposed probabilistic based analytical approach for reliability assessment of distribution systems containing renewable DG units. It also presents the detailed modeling of system restoration and the associated calculation procedures. The simulation results are reported in Section IV and comparative results are presented for verification of the proposed method. Section V summarizes the major research contributions of this paper.

II. Reliability Assessment of DG Enhanced Distribution Feeders

In this section, an analytical formulation for evaluating system reliability in terms of system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) is presented. A partitioning concept is formulated based on the reliability zone concept presented in [14] and the segmentation concept given in [12], and is incorporated in the development of the proposed analytical method, to reduce the overall computational burden without sacrificing the accuracy of the assessment. The proposed method is developed for reliability evaluation of renewable DG enhanced distribution feeders, while paying specific attention to DG side restoration.

A. Partitioning Concept

For effective assessment of overall system reliability, a sample distribution network as shown in Fig. 1 can be partitioned into reliability equivalent zones based on the locations of the system protection devices such as circuit breakers, manual switches, fuses, etc. The loads distributed in a partitioned reliability zone can be seen as a single load point with aggregated load demand served by various feeder sections (such as F1, F2, F3, F4, and F5). The sustained failure rate for a partitioned reliability zone can be calculated, using the summation of individual failure rates for different components embedded inside the zone, as given in

$$\lambda_z^{\mathrm{zn}} = \sum_{c=1}^{N_z^{\mathrm{cp}}} \lambda_{c,z}^{\mathrm{cp}} \tag{1}$$

where λ_z^{zn} is the sustained failure rate of the partitioned reliability zone z, N_z^{cp} is the total number of components in the zone z, and $\lambda_{c,z}^{\mathrm{cp}}$ is the sustained failure rate of component c in the zone z.

The average repair time R_z^{zn} for a fault in the partitioned reliability zone z can be calculated as

$$R_z^{\mathrm{zn}} = \frac{1}{\lambda_z^{\mathrm{zn}}} \sum_{c=1}^{N_z^{\mathrm{cp}}} \lambda_{c,z}^{\mathrm{cp}} R_{c,z}^{\mathrm{cp}} \tag{2}$$

where $R_{c,z}^{\mathrm{cp}}$ is the repair time of component c in the zone z.

B. Calculations of SAIDI and SAIFI

In case of a fault, in a partitioned reliability zone, the whole distribution feeder can be typically divided into three areas as illustrated in Fig. 1. Area-1 is defined as the area where the customers can be reconnected to the substation as soon as the fault is isolated. In Area-2, the customers can only be reconnected to the substation after repairing the faulty component in the reliability zone. The customers involved in Area-3 can be reconnected to the renewable DG system during the repair period with a proper restoration scheme. With the consideration of customer interruption durations and frequencies in these three areas, the overall system reliability in terms of SAIDI and SAIFI can be calculated as

$$\mathrm{SAIDI} = \frac{1}{N^{\mathrm{cst}}} \left(\sum_{z=1}^{N^{\mathrm{zn}}} \lambda_z^{\mathrm{zn}} \left(D_z^{\mathrm{flt}} + D_z^{\mathrm{sub}} + D_z^{\mathrm{dg}} \right) \right) \tag{3}$$

$$\mathrm{SAIFI} = \frac{1}{N^{\mathrm{cst}}} \left(\sum_{z=1}^{N^{\mathrm{zn}}} \lambda_z^{\mathrm{zn}} \left(F_z^{\mathrm{flt}} + F_z^{\mathrm{sub}} + F_z^{\mathrm{dg}} \right) \right) \tag{4}$$

where N^{cst} is the total number of customers in a distribution network, N^{zn} is the total number of reliability equivalent zones in a distribution network, D_z^{sub}, D_z^{flt}, and D_z^{dg} are the customer interruption durations and F_z^{sub}, F_z^{flt}, and F_z^{dg} are customer interruption frequencies associated with the customers in Areas 1-3, respectively.

1) Calculations of D_z^{sub} and F_z^{sub}: Some of the customers that can be reconnected to the substation may experience momentary interruptions, especially, if a fault can be isolated by automated switching or fuse. On the other hand,