Techniques for Reliability Evaluation in Distribution System Planning

T. Lantharthong, N. Phanthuna

Abstract**—**This paper presents reliability evaluation techniques which are applied in distribution system planning studies and operation. Reliability of distribution systems is an important issue in power engineering for both utilities and customers. Reliability is a key issue in the design and operation of electric power distribution systems and load. Reliability evaluation of distribution systems has been the subject of many recent papers and the modeling and evaluation techniques have improved considerably.

Keywords**—**Reliability Evaluation, Optimization Technique, Reliability Indices

I. Introduction

THE basic function of an electrical power system is to meet its customers while maintaining acceptable levels of quality and continuity of supply [1]. It is important to note that the distribution system is a vital link between the bulk power system and its customers. In many cases, these links are radial in nature that makes them vulnerable to customer interruptions due to a single outage event. A radial distribution circuit generally uses main feeders and lateral distributors to supply customer energy requirements. In the past, the distribution segment of a power system received considerably less attention in terms of reliability planning compared to generation and transmission segments. The basic reason behind this is the fact that generation and transmission segments are very capital intensive, and outages in these segments can cause widespread catastrophic economic consequences for society [2].

An electric power system comprises generation, transmission and distribution. It is also necessary to ensure a reasonable balance in the reliability of these various constituent parts [3]. Electric power distribution systems constitute the greatest risk to the interruption of power supply [4]-[6]. It has been reported in the literature that more than 80% of all customer interruptions occur due to failures in the distribution system. The distribution segment has been the weakest link between the source of supply and the customer load points. Though a single distribution system reinforcement scheme is relatively inexpensive compared to a generation or a transmission improvement scheme, an electric utility normally spends a large sum of capital and maintenance budget collectively on a huge number of distribution improvement projects [2].

At present, in many electric utilities, acceptable levels of service continuity are determined by comparing the actual interruption frequency and duration indices with arbitrary targets. For example, monthly reports on service continuity statistics produced by many utilities contain the arbitrary targets of system reliability indices for performance comparison purposes. It has long been recognized especially in the deregulated market environment that rules of thumb and implicit criteria cannot be applied in a consistent manner to the very large number of capital and maintenance investment and operating decisions that are routinely made. Though some reliability programs with limited capabilities are available, virtually no utilities perform distribution system expansion studies using probabilistic models.

Distribution utilities are required only to furnish historical distribution system performance indices to regulatory agencies [2]. Reliability evaluation and maintenance planning techniques have separately been well developed, for example [4]-[7], However, few techniques relate system reliability to component maintenance. Furthermore, the available techniques are not generally put into practice. The reason for this, according with the authors, is the lack of suitable input data and a reluctance to use theoretical tools to address the practical problem of maintenance planning [8]. A great problem encountered in the area of distribution systems is how to reduce the number of interruptions experienced by customers. At first, these reductions can be obtained with the substitution of the equipment with the high failure rates and by increasing the maintenance staff. Usually, these are very expensive solutions. The automation of the protection has proven to be a feasible and efficient alternative to solve this problem [9]. A reliability evaluation can be used to evaluate past performance and predict future performance of the distribution system. A reliability evaluation study can also identify the problematic components in the system that can impact reliability. The reliability study can also help to predict the reliability performance of the system after any expansion and quantify the impact of adding new components to the system. The number and locations of new components needed to improve the reliability indices to certain limits can be identified and studied [10].

II. Reliability Indices System

Reliability indices of an electric distribution system are functions of factors such as component failures, repairs and restoration times which are random by nature. These indices are, therefore, random variables and can be described by probability distributions. The mean values of the probability distributions associated with the reliability indices are very useful and conventional reliability analysis is normally only concerned with these values. There is, however, an increased awareness of the need to evaluate parameters which give

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information regarding the variation of the indices around their mean value [4].

The basic distributed system reliability indices at a load point are average failure rate λ, average outage duration *r*, and annual outage duration *U*. With these three basic load point indices, the following system reliability indices can be calculated [4].

Average interruption frequency index (SAIFI)

$$SAIFI = \sum \frac{\lambda_i N_i}{N_i} \tag{1}$$

System average interruption duration index (SAIDI)

$$SAIDI = \sum \frac{U_i N_i}{N_i} \tag{2}$$

Customer average interruption duration index (CAIDI)

$$CAIDI = \sum \frac{U_i N_i}{\lambda_i N_i} \tag{3}$$

Average service availability index (ASAI)

$$ASAI = \frac{\sum N_i \times 8760 - \sum U_i N_i}{\sum N_i \times 8760} \tag{4}$$

Average service unavailability index (ASUI)

$$ASUI = 1 - ASAI = \frac{\sum U_i N_i}{\sum N_i \times 8760} \tag{5}$$

Energy not supplied index (ENS)

$$ENS = \sum L_{a(i)} U_i \tag{6}$$

Average energy not supplied index (AENS)

$$AENS = \frac{\sum L_{a(i)} U_i}{\sum N_i} \tag{7}$$

III. Reliability Assessment in Distribution System

A. Distributed Generation (DG)

The nature of today's distribution grids is changing from passive to active. The penetration level of distributed generation units (DG units) is increasing and it is expected that this growth will continue over the next years. At the moment not only the number of DG units is increasing, but also, in specific areas, the size of the units. In this way, in the near future, the DG may contribute in a substantial part of the power generation. DG technologies can be categorized in renewable and nonrenewable [11]. Examples of renewable technologies are, e.g., solar, wind, and geothermal, while examples of nonrenewable technologies are internal combustion engines, microturbines, and fuel cells. Two most popular and widely used DG schemes are [12].

- Wind turbines.
- Combined heat and power (CHP) plants.

These review papers have provided a general background of reliability research in Distribution System. The concept of segments, which has been applied in previous reliability studies, is used in the DG placement [13]. The optimum locations are sought for time-varying load patterns. It is shown that the circuit reliability is a function of the loading level. The difference of DG placement between optimum efficiency and optimum reliability varies under different load conditions. Observations and recommendations concerning DG placement for optimum reliability and efficiency are provided. In [14] presents a reliability model for determining the DG equivalence to a distribution facility for use in distribution system planning studies in the new competitive environment. Impacts of DG implementation on distribution system reliability are investigated using a distribution test system. A reliability model for DG is developed and an analytical probabilistic approach is proposed for this purpose. Impacts of different parameters such as components failure rates, load and DG positions and DG generation parameters are included in the analysis [15].

In [16] is a new alternative in limiting the fault current recently increasing in a network. An evaluation technique for distribution reliability that uses the improved failure rate of all protective devices in a network, depending on the location of the superconducting fault current limiter (SFCL), is also proposed. As a result, it is expected that the SFCL makes the reliability of adjacent equipment on an existing network improve, and these changes are analyzed. In addition, in order to apply the effect of the intermittent output of renewable-energy sources, distribution reliability indices were redefined. Case studies verify that the SFCL is effective in reducing fault currents and improving distribution reliability. These effects are analyzed with respect to the location of the SFCL in a case study system.

P. Wang and R. Billinton [17] presented the system reliability benefits of adding wind turbine generation (WTG) as alternative supply in a rural distribution system. The wind generation interrupted energy benefit (WGIEB), the wind generation interruption cost benefit (WGICB), the equivalent number of conventional generators (ENCG) and the equivalent conventional generator capacity (ECGC) of one MW WTG are introduced. These indices provide direct reliability benefit indicators on the addition of WTG, and are important information for system planners to make planning decisions such as the selection of a wind site and the number of WTG. A test rural distribution system is utilized to illustrate the proposed technique. The effects on the system reliability benefits of the wind site selection and the number of wind units are investigated [18].

Increasing exploitation of wind energy requires the development of adequate models and techniques for reliability assessment of wind farms (WFs) and of electric power systems including wind energy conversion systems. A novel approach to WF modeling is investigated for reliability assessment, which is based on the universal generating functions. Such an approach combines the use of the z-transform and composition operators, allowing to account for all the factors affecting the WF performance. The results, both theoretical and numerical, of the case study, give evidence of the effectiveness of the proposed approach in terms of accuracy as well as of flexibility and efficiency of the solving algorithm. L. Wang [19] presents an alternative option, four representative population-based intelligent search (PIS) procedures including genetic algorithm (GA), particle swarm optimization (PSO), artificial immune system (AIS), and ant colony system (ACS) are adopted to search the meaningful system states through their inherent convergence mechanisms. These most probable failure states contribute most significantly to the adequacy indices including loss of load expectation (LOLE), loss of load frequency (LOLF), and expected energy not supplied (EENS). The proposed solution methodology is also compared with the Monte Carlo simulation through conceptual analyses and numerical simulations. In this way, some qualitative and quantitative comparisons are conducted. A modified IEEE Reliability Test System (IEEE-RTS) is used in this investigation.

B. Modeling of Distribution System

Modeling the component reliability for representative electrical components due to electrical stress, mechanical stress, temperature and time, which takes general aging mechanisms of insulating materials into consideration; proposed models provide reliability estimates, e.g. failure probability and failure rate for distribution systems. These models can be not only parameterized with a great deal of statistical data but also determined by aging tests and breakdown tests being available for the probabilistic assessment [20]. Our results imply that the assessment approach for component reliability will motivate a need for reasonable and accurate data at an early decision-making stage in future deregulation of electric power market. R**.** E. Brown [21] presents a new method, termed Hierarchical Markov Modeling (HMM), which can perform predictive distribution system reliability assessment. HMM is unique in that it decomposes the reliability model based on system topology, integrated protection systems, and individual protection devices. This structure, which easily accommodates the effects of backup protection, fault isolation, and load restoration, is compared to simpler reliability models. HMM is then used to assess the reliability of an existing utility distribution system and to explore the reliability impact of several design improvement options. W. Li, and et al. [22] presents a new method for load modeling in power system reliability evaluation.

The method combines the fuzzy model for the peak load with a probability distribution for a load curve, whereas system component outages can still be modeled using traditional Monte Carlo or enumeration techniques. R. H. Stillman [23] presents a methodology in which a distribution system is modeled as a repairable system.

The reliability of two systems are compared, a widespread rural system, and a large urban network. A comparative analysis is made to determine if the inter arrival times of system failure events appear exponential and as such, can be modeled as a homogenous poisson process (HPP), or whether these should be treated as events of a non homogeneous poisson process (NHPP), as defined in [1]. It is argued that to treat the inter arrival times of system failure events as being independent of the history of the system (the HPP model which is commonly adopted) leads to a misunderstanding of the system reliability state, which in turn impacts on the management of maintenance and replacement criteria.

H. Kim, [24] illustrates the effects of aging in reliability modeling. To implement the history of working and failure of system, stochastic point process modeling based on sequential Monte Carlo simulation is proposed. In the proposed method, the concept of thinning is used for non-homogeneous poisson process characterization of lifetime of aging components. This simulation technique is applied to the single area IEEE radial distribution system and the results are compared.

The physical environment in which a transmission and distribution system resides has a significant impact on the resulting reliability of the network. The inclusion of weather conditions in the reliability analyses of transmission and distribution systems is discussed [25]. A series of weather models is presented with application to a practical transmission/distribution system. The conventional approach to predictive reliability assessment using single-and two-state weather models is briefly illustrated.

A three-state weather model is presented to incorporate failures occurring in major adverse weather conditions. The system reliability indices obtained using the weather models clearly show the need to incorporate weather effects into reliability analyses. Results obtained without weather considerations can be quite misleading and optimistic. In [26] presents reliability modeling and analysis of an HVDC transmission system incorporating a voltage-sourced converter (VSC) tapping station. The use of VSC tapping stations enables the supply of power along the route to areas with comparatively little consumption. Using this equivalent reliability model, various reliability indices are calculated at the load point of the system and the impacts of the VSC tapping station on these indices are illustrated. Sensitivity analyses are conducted to investigate the impacts of the load level and the location of the tapping station on the reliability indices.

The conducted studies are numerically applied on a typical HVDC system and thorough discussions are presented. R. E. Brown [27] examines three aspects of substation reliability modeling. It first compares substation reliability models of varying complexity. It then performs a sensitivity analysis of substation reliability to component reliability parameters. Last, it develops an equivalent distribution substation model that can be used with feeder reliability models to compute overall distribution system reliability [28]. This method results in accurate composite system reliability results, but allows substation reliability analysis and feeder reliability analysis to be decoupled.

IV. Conclusion

This paper has reviewed some aspects of reliability research in distribution systems in the following three main topics:

- Introduction of concepts of reliability in distribution system
- Reliability indices system
- Reliability Assessment of distribution system

Techniques for reliability evaluation are important in the planning and operation of distribution system. Operation and maintenance costs due to low reliability can be reduced by adequate planning, monitoring system behavior and taking proper control actions.

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