Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 08, August-2016

A Survey on Methods of Evaluation of Reliability of Distribution Systems with Distributed Generation

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***Abstract*— With the growth of economy and society, consumers of electricity are demanding supply of more reliable electricity that needs a superior performance of power system. Distributed Generation (DG) sources have obtained a lot of consideration in modern times because of their positive impact on the reliability of distribution system. System and load point reliability indices are found to be improved if DG is employed in distribution network. This article makes an effort to review different methodologies and techniques employed for the evaluation of reliability of distribution system when integrated with distribution generation (DG). Various techniques employed by different authors are analyzed, which are divided mainly into three categories: analytical techniques, Monte Carlo simulation and other probabilistic techniques. It is found that most of the studies in reliability of distribution systems with DG in the literature are formulated for specific study - systems.**

Keywords – Distributed power generation, Distribution system reliability, Monte Carlo simulation, Reliability evaluation.

I. INTRODUCTION

The aim of a power system is to supply power in cost-effective and reliable manner. It is essential to plan and maintain reliable electrical power systems because price of interruptions and power failures can have very bad financial impact on the utility and its consumers. The reliability of power distribution system is main issue in planning and working of the system. Reliability assessment is of prime importance in planning and designing of distribution systems that operate in a cost-effective manner with minimum interruption of customer loads. From the available reports in literature, it is understood that nearly 85% of interruptions of customers take place due to the distribution system failures. Hence, the reliability of distribution systems is considered as one of the more important issues from the technical as well as economical point of view. Further, there are regulations based on the performance, introduced by the regulation authorities in different countries. Hence, the utility company will search for means to reduce costs and also supply the satisfactory level of reliability for its customers, to remain competitive.

II. DISTRIBUTED GENERATION

Distributed generators are small scale power sources (10 MW or less) installed on the consumer terminal, and provide power independently for a few customers and are able to provide power in association with public distribution. Some examples for DGs are fuel cells, wind turbines, micro turbines, PV cells, IC engines and renewable sources etc. Distributed generation has specific advantages in supporting the power distribution systems, reducing energy consumption, saving investment, utilizing new energy and enhancement in the reliability and flexibility. It is generally used in the distribution network. With advances in technology, usage of distributed generation in the power distribution networks is increasing. Employing DG into the power system poses several challenges in interconnection, protection coordination and voltage regulation. But increased reliability and cost reduction are the primary advantages of adding DG into a power system.

III. CONTRIBUTION OF DG FOR RELIABILITY

DG technologies are having a great impact on high-reliability applications, as source of capacity during emergency or as a means of deferring the extension of a local network. DG can be made available during power system failure to guarantee a more reliable supply. The major direct role of DG to reliability is on the consumer side. The level of reliability is boosted since the local load is supplied by DGs during interruptions. When a stand by DG is connected, the durations of interruptions are lesser. The system reliability is improved by the presence of DG in the distribution system since it supplies loads in the islanding operation.

IV. RELIABILITY EVALUATION OF DISTRIBUTION SYSTEMS

The Evaluation of Reliability of the distribution system is based on a number of reliability indices like Average Failure Rate λ, Average Interruption time U, Average Interruption duration time r, System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 08, August-2016

(SAIFI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI), Average Service Unavailability Index (ASUI), Expected Un served Energy(EUE) and Expected Outage Cost(EOC).

There are several techniques used in the analysis of power system reliability. These techniques are usually divided into the two main categories: Analytical approaches and Monte Carlo Simulation techniques or it could be the combination of these two techniques.

Analytical approaches make use of mathematical models for evaluation of the reliability of electrical distribution systems. The analytical approach based on contingency enumeration can identify low voltage and voltage collapse problems in addition to thermal overloads. But the enumeration approach cannot model a wide range of operating conditions and hence is subject to various simplifying assumptions.

But Monte Carlo simulation is capable of modeling the entire range of operating conditions. Monte Carlo simulation has several advantages in reliability evaluation of distribution system, which is more evident when DGs are extensively introduced into the distribution system. Monte Carlo simulation avoids the different operation issues introduced by DGs. Furthermore, Monte Carlo simulation can better explain the uncertain properties of DGs. It is also easier to discuss several accidents when applying Monte Carlo simulation. One drawback of this model is that limitations of computer resource limit the precision of solution to dc power flow problems. In this case, the simulated performance indices indicate only overloading problems of the system. But the low-probability transmission outages and low voltage and voltage collapse problems cannot be modeled in this technique.

Hence the survey conducted on the evaluation of reliability can be classified into three categories: 1. Evaluation based on Analytical methods. 2. Evaluation using Monte Carlo simulation and 3. Evaluation based on other methods.

V. RELIABILITY EVALUATION BY USING MONTE CARLO SIMULATION

A new method has been proposed for reliability evaluation of active distribution systems with multiple micro grids based on Monte Carlo Simulation (MCS) in [1]. Different types of distributed generators are represented by developing multi-state models based on generalized capacity outage tables for reliability evaluation.

The micro grids with intermittent sources are modeled by introducing the virtual power plant (VPP). The reliability behavior of VPP is characterized by an equivalent GCOT efficiently. The non sequential Monte Carlo technique is then used for the assessment of reliability of active distribution systems for different modes of operation with single or multiple contingencies.

A two-hierarchy MCS technique is proposed to estimate the reliability of active distribution networks on both the micro grid and main grid levels. Two step sampling, zone partitioning and minimal path search techniques are used to accelerate the state sampling and evaluation process in the MCS. In [2], Depth-First Search algorithm is used to divide the distribution system into numerous smallest units to improve traversing speed. The defective network is converted into the Islanding operation mode automatically, to increase the reliability of the system. The probability model of network components is proposed and the status of Distribution System with DG is simulated by using MCS Method and the reliability of the system is quantitatively estimated.

A new methodology which is based on a combination of analytical techniques (minimal cut-sets) and chronological MCS to evaluate the effect of distributed energy recourses on the reliability indices of distribution systems is discussed in [3]. It estimates the capacity that can be transferred to other feeders, considering the presence of DG. This methodology is tested on a typical Brazilian distribution system considering the integration of a diesel-based unit, wind turbines, and solar panels. The results are presented and discussed considering the reliability benefits of employing distributed energy resources to improve load transfer limitations. But the Impacts of DG on power quality, transmission losses, voltage stability etc. are not considered. A systematic method based on system well-being analysis framework is utilized [4] to obtain the two elementary aspects of power system reliability, known as adequacy and security, of a power system having winding power generation. A sequential MCS technique has been used to accurately integrate the chronology of intermittent wind generation and to illustrate the system well-being index probability distributions in addition to the expected values. The results of adding wind power generation and conventional generation have been presented and compared by using numerical results and probability distributions. The system well-being analysis presented in the work is a significant extension of the usual approach to the assessment of generating system adequacy to consider the system security constraint. It provides a visual representation of a multi-dimensional risk assessment approach that complements the single risk dimension provided by an expected value.

Based on the concept of segmentation, four types of data structures are introduced to represent the topological structure and parameters of the distribution system [5]. The power interruption time of each load point is calculated by using the area division and load optimization, and the reliability indices are calculated for a small reliability test system. The article proposes the sequence model of DGs and the load by assuming that the basic unit for changes in power is an hour. It divides the system into various types of area on the segmentation concept, and obtains the synchronous sampling of load size DG output and DG output by time sequential MCS. The role of DGs in the improvement of reliability of distribution system is verified by comparing the reliability indices before and after the connection of DGs into the test system. Hence the rationality of evaluation of reliability is improved by the proposed method. The data structures explained in this paper can bring great ease to the reliability evaluation.

The distribution network reliability under islanded micro grid and grid-tied modes is evaluated in [6]. The stochastic models of PV and WT have been used to simulate the intermittent nature of the wind speed and solar insolation. The time varying load model has been developed to make the study

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ISSN: 2278-0181
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realistic. A MCS has been used to calculate the reliability indices of RBTS Bus-2 with and without having micro grids. The effect of islanded operation on the reliability of distribution system is analyzed. A new method has been introduced by applying MCS for the assessment of system failure state, based on zoning and minimal path concepts and the reliability of the distribution system with DGs are calculated [7]. The impacts of DGs on the distribution system are studied by using an example based on IEEE-RBTS Bus-6. A lot of elements such as models of DGs, multiple accidents, switch devices configuration and islanding strategies are taken into consideration. But this discussion does not focus on the probable relation between islanding schemes and multiple accidents, which requires further study. Since the results of reliability calculation in the example are based on the non-sequential Monte Carlo method, precise frequency indexes are not available.

A methodology for evaluation of reliability of distribution systems with distributed generation (DG) based on different energy sources is proposed in [8]. It takes into consideration the possibility of DG connection at the High Voltage (HV) and Medium Voltage (MV) buses of the distribution substation, and also the MV distribution network. The uncertainty in availability of energy of time varying sources, like the wind generation, and the sequential variation of the loads are incorporated in the methodology. The non-intermittent energy sources such as gas and oil DGs, are represented by a multiple states Markov model. For wind generation two different models are used. One model combines the two states Markov model of wind turbine with the stochastic wind turbine model. The other which is a chronological model combines the time series of wind, the characteristic of wind turbine generation and the generator failure probability. The load variation model used is obtained by using fuzzy sets and neural networks. For the LV consumers, yearly load curve of the distribution transformer to which the customers are connected is used to represent the load. For the MV customers, the load is represented by the annual load characteristic constructed by using its daily demand characteristics. The evaluation of system reliability is obtained using Sequential MCS.

A new methodology which simulates the functioning of distribution networks with DG and estimates the status of load demand and reliability of the system has been presented in [9]. A flexible and proficient simulator is developed to execute this methodology. A variety of additional features like multiple distributions for the distribution and supply line failure and repair charges and stochastic load characteristics have been included. The methodology uses a sequential MCS for stochastic model of the distribution system to create the operating behavior. This is integrated with a path augmenting Max flow algorithm to estimate the load status for each change of state of operation of the system. General system and load point reliability indices like hourly loss of load, frequency of loss of load and expected energy un-served can be evaluated by using this technique. The methodology presented in this paper uses the Ford-Fulkerson algorithm to find out the flows in the network and assess the load demand condition for each state of operation of the system. Different cases of supply level distribution systems with different number of DGs have been studied to investigate the impact of DG on reliability of the network at system level and at particular load points.

VI. RELIABILITY EVALUATION BY USING ANALYTICAL METHODS

A novel universal systematic approach along with the associated analytical formulation is presented in [10] to evaluate reliability of distribution system in the context of a multi-micro grid smart network. Also, a new method is presented to compute the adequacy of micro grid with conventional and renewable DGs by taking into account load shedding and restrictions. Reliability indices have been worked out for the RBTS-BUS6, both when island operation is assumed to be possible and when it is not possible. Using the proposed procedure, it has been shown that in the case, such an advanced network paradigm can significantly improve local and overall reliability. But the proposed procedure is based on the assumption that an advanced automation and protection scheme is available in order to avoid conflicts between DGs interface and network protections, as well as to allow that the switches closest to the fault trip first. Hence there is further scope for the development of procedures to calculate the reliability when the switches are not fully reliable. The adequacy of a radial distribution system having various types of DG units has been assessed for different modes of operation by using an analytical technique [11]. The load behavior has been modeled using IEEE-RTS system and by creating the multi-state availability models of all the generating units. Also, the impact of islanding mode of operation on system adequacy from the point of view of Loss of Load Expectation (LOLE) and Loss of Energy Expectation (LOEE) has been measured. The validity of the analytical technique is checked by using MCS technique. The results obtained show no major difference between the outcomes of the two proposed methods. Moreover, it is found that incorporating DG units with the system has a significant impact on the enhancement of the system adequacy, and islanded mode of operation also adds to the improvement of adequacy. Paper [12] analyzes the impact of DGs running in three different modes, which are back up mode, in parallel with main grid and as a micro grid on reliability and applies the methods of reliability analysis respectively. A technique for assessing the reliability of the distribution system involving DGs based on traditional reliability evaluation technique has been proposed. The technique used to evaluate reliability of distribution system is based on usual failure mode and effect analysis. In [13], an analytical method has been proposed to study the DG impacts on reliability indices of distribution systems. The approach involves intrinsic attributes of both DG and distribution system, such as failure of the DG components, change in the DG resource, and change in the load demand. An analytical probabilistic method is proposed for this, after developing the reliability model for DG. The probability of islanding is calculated for the failure of each segment of the distribution feeder. Both DG and load demand are incorporated in calculation of islanding probability. A technique to evaluate the distribution system reliability including distributed generation, by means of the load duration curve has been

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 08, August-2016

presented in [14]. The proposed procedure considers the stand by and peaking modes and also their mixed operation mode. For the purpose of general application in connection matrices, the equations have been developed. The reliability indices with MCS, using the hourly load model are compared by conducting case studies. It is found that the results of the proposed analytical method are almost equivalent to that of MCS. A probabilistic based analytical method is formulated to estimate reliability of the system in terms of system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI) for distribution system involving non-dispatchable and dispatchable renewable DG units [15]. The proposed technique has been developed by implementing restoration of DG side with complete technical considerations, involving DG unit failures, time-dependent patterns of load demand and power output of DG, and two-stage and single-stage restoration. From the results of simulation, it is found that the results obtained by the proposed analytical technique are almost comparable to those derived by MCS and better than those calculated using present analytical methods existing, in all the cases.

Paper [16] presents an algorithm based on analytical approach for evaluating restoration time of distribution system load points with DG units used as backup generation. Many system indices such as SAIFI, CAIDI, SAIDI and AENS are calculated for a real radial distribution system. A sensitivity analysis is conducted to study the impact of DG units, their number and their location on reliability indices. The results show that when DG units are incorporated as standby units, they only affect duration of outage and not frequency of interruption and hence SAIFI will be unchanged. The results also illustrate that indices are very sensitive to number, location, and availability of DG units. Hence, using the proposed method the optimum number of DG units for the best location in distribution system can be obtained. In [17], the method used to calculate reliability indices with and without installation of DGs in a radial distribution system has been presented. The paper proposed the estimation of restoration time and the impact of customer scattering on reliability of distribution system when DG unit is implemented at different locations. The system reliability indices assessed by the algorithm presented incorporated SAIFI, ENS SAIDI, AENS and CAIDI, for 6 cases of customer scattering and for 9 possible locations of DG. The results obtained showed the optimal location of DG for every pattern of customer scattering in terms of reliability evacuation. It is found that SAIFI is constant for all cases of customer scattering, because assessment of restoration time does not affect the frequency of interruption of the distribution system. The best locations of DG for SAIDI and CAIDI improvement changed with the type of customer scattering. The AENS and ENS depended on the locations of DG only and not on the customer scattering patterns. This analysis can be utilized to recognize the optimal location of DG employed as backup generator in a distribution system, to improve reliability indices depending on customer scattering. The results indicate that the restoration time and customer scattering affect the optimal location of DG units.

Paper [18] introduces a new simplified and intuitive analytical technique for assessment of load point indices and system indices when DG is connected to the system to find the role of the DG in the improvement of reliability of the system. The distribution system has been modeled for reliability calculations including these DG units. Reliability evaluations are analyzed in a case study for an original distribution system configuration : with and without DG. One of the major advantages of this technique is that it is computationally efficient. The results are combined to produce the system and load point indices for two simulations. The method is suitable to ring systems. Another advantage is that it avoids the necessity of special devices in reliability algorithms for not including the DG twice and even in the protection algorithms to create the essential actions for restoring power.

VII. RELIABILITY EVALUATION BY USING OTHER METHODS

An evaluation of adequacy and security of distribution systems considering islanded operation of DGs is illustrated in paper [19]. It proposes a method which employs a combined discrete-continuous simulation model to study dynamic and steady state behavior of the system operation and to assess the load point and system reliability indices. Also under voltage/overvoltage information is integrated in terms of performance indices. A Markov model proposed in [20] assesses the reliability of a future networked distribution system containing conventional or renewable DG units. The analysis of reliability is achieved by using an encoded Markov cut set (EMCS) algorithm. An integrated Markov model which incorporates the transition rate of DG adequacy, DG mechanical breakdown, and switching and starting probability is planned and utilized to give precise results for the assessment of DG reliability. To model the impact of the DG on reliability, all the components or failure modes which are associated with the operation of the DG during faults are integrated into the reliability model of DG unit. The system adequacy of DG in islanded mode is evaluated and included in the reliability assessment.

A probabilistic technique to assess the reliability of the distribution system with wind-based DGs during the islanding mode of operation using segmentation concept is presented in [21]. A novel constrained Grey predictor procedure is applied for estimating wind speed profile evaluation. Also, the impact of altering the wind penetration on the reliability of the system is studied by carrying out the sensitivity analysis. An optimization problem called the feeder addition problem is stated to decide possible locations for adding interties amid feeders in a radial distribution system to enhance the reliability in the islanded mode of functioning [22]. A heuristic method called the sequential feeder technique and a multipurpose Genetic Algorithm were used to resolve the optimization of feeder addition in an islanded distribution system with DGs, taking into consideration the cost and reliability which were calculated using a slack bus-based statement of ENS. The power output of the DG sources considered is approximated using an empirical equation involving the capacity factors of renewable energy-based DGs and industry survey results. It

International Journal of Engineering Research & Technology (IJERT)
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can be found that both optimization methods improve the system reliability. It is projected that the techniques presented in this paper can be used as a means for planning the improvement of reliability of the distribution system.

The reliability of distributed generation system is evaluated by implementing software called Distributed Industrial System Reliability Evaluation algorithm (DISREL) for validating the reliability evaluation module and is tested on a 32-bus distribution system by simulating for various case studies in [23]. The reliability of distribution system is assessed based on a variety of reliability indices. The effect of DG on distribution systems during contingency was analyzed by implementing DG as a control action for reducing overloaded lines thereby enhancing system reliability and improving security.

The distribution system reliability with wind generators is assessed by applying the network-equivalent approach in [24]. The uncertainty of wind power caused by wind speed is examined by dividing wind speed into intervals explained by the interval probability and mean output. Then the importance of load is studied by classifying loads into different grades, each with separate weight coefficients. Reliability indices are evaluated considering load importance and uncertainty in wind generation, which reveals the notable influence of wind power on reliability of distribution system. The reliability indices are compared with those before considering wind power uncertainty and load importance, which shows the significant improvement that wind generation can make on reliability of distribution system. It is noted that the wind generators can satisfy customers only within the limits of their capacities according to load importance. Since wind generators give priority to important customers, the reliability indices of less significant customers can not improve; due to insufficient wind power.

In paper [25] credibility theory is applied to assess the distribution network reliability. This technique models both subjective and objective uncertainties. Failures of equipments are modeled as random procedures, while the failure indices uncertainty is modeled by employing fuzzy set theory. Hence reliability of distribution system is assessed by considering objective and subjective uncertainty simultaneously. In this paper, a hybrid algorithm based on Failure Mode and Effect Analysis (FMEA) and fuzzy simulation and is employed to find out fuzzy reliability indices of distribution system. This method can obtain fuzzy expected values of reliability indices and their variances, and the credibility of reliability indices in reaching specific targets. The method proposed gives information regarding the indices by illustrating the way in which the indices are dispersed, rather than simply obtaining their expected values. This provides a better sense of achievable reliability targets, during planning and operation.

A presentation about modeling of reliability aspects of distributed generation integrated into distribution network is discussed in [26]. Three different models created were presented. The first one is based on analytical approach and is employable for non-intermittent energy source DGs. The second one takes into account the uncertainty of generation involved in wind generation and introduces a model based on multiple states Markov process. The third model combines some features of the two earlier models and integrates the load duration curve in a sequential MCS technique. Practical operational locations are taken into account in all models. In a broad sense, the paper concludes that DG improves the distribution systems reliability, particularly in cases where islanding is considered.

Paper [27] introduces a methodology for assessing the probabilistic reliability, taking into consideration web based on a daily interval reliability information system for a grid controlled complex power system involving wind generators (WG). The model proposed makes use of a multi-state model of a generator to deal with WG, got by combining the power output model of WGs and wind speed model. It also considers transmission line unavailability, capacity limitations and the operation of WG modeled by multi-states. A web based online real time reliability integrated information system (WORRIS) is employed using the methodology presented in this paper. An interval algorithm is presented [28] to consider the uncertainty of component data to evaluate the interval reliability indices. In this paper, interval mathematics is applied to assess the distribution system reliability indices dealing with the uncertainty of primary parameters. In order to find out the impact of DG on improvement of reliability of distribution system, RBTS bus6 system is taken as an example and the reliability indices are calculated before and after the addition of DG into the system. In the meantime, the impacts of different locations of DG on distribution system are also studied. The simulation results show that interval algorithm and mathematical model chosen can precisely evaluate the reliability indices taking into account the uncertainty of primary parameters. A critical review of a variety of techniques which are used to address the siting and sizing of Distributed generation in view of different objectives is presented in [29]. The different techniques reviewed are grouped as Analytical techniques, Heuristic techniques, Meta heuristic techniques, Genetic Algorithm and Genetic algorithm hybrid approach. Depending upon this review it can be concluded that analytical techniques may not be suitable for complicated problems, meta-heuristic and heuristic techniques
offer a more simplified and feasible solution. However this may direct to a compromise in quality of solution and computational time. A hybrid of two or more techniques can suggest a better option by involving the benefits of techniques and avoiding the drawbacks. Paper [30] presents a new model and procedure for studying the reliability of distribution network by considering the effect of the WPDG. It discusses the island's interruption time and rate of failure during different modes of functioning of the WPDG, and explains an optimization policy known as under-frequency load shedding in the island and makes the reliability model more precise. By using the example of RBTS-Bus 6, it compares 4 cases: as without DG, with the WPDG, with the WDG and the PDG respectively. It proves that the WPDG is more competitive in improving the reliability of the distribution network system. It applies the technique of failure mode and effect analysis (FMEA) for evaluating the reliability.

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ISSN: 2278-0181
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The basic purpose of [31] is to introduce a probabilistic reliability model to establish DG equivalence to a distribution network for improving the reliability of the distribution system while supplying increasing requirements of customer load. General Reliability's DISREL program has been employed to determine DG equivalence to the addition of a third feeder to the region. DISREL calculates a set of reliability indices like SAIFI, ASAI, SAIDI, load curtailed, and the rate of outages depending on the component outage data and the interruption cost to a customer. The program has modeled time-sequenced switching operations performed by an operator subsequent to an outage. It can also be applied to quantify advantages of automating distribution networks, reconfiguration of feeders, and to compare different competing projects by means of rate of outages and benefits for utility. Typical interruption data for main components and the cost of outage data for various types of consumer are supplied with the DISREL program. The methodology can be efficiently applied in the competitive electric energy market to assess a wide variety of power system problems.

VIII. CONCLUSIONS

This paper has presented a critical review of various techniques which have been employed to evaluate the reliability of distribution systems when distributed generation is employed. The analysis has revealed that the literature does not present an automated generalized algorithm to estimate the reliability of distribution systems including renewable DGs. Most of the studies in DG reliability in the literature are individually formulated and employed to certain study-systems. There is no generally available method to forecast the reliability of distribution systems with distributed generation. Also there is a lack of assessment methodologies to evaluate the real impact of DGs on distribution systems. Hence, a new methodology is necessary to deal with the problems faced by the distribution system planners currently. Hence, the work is in progress with an objective to model the distribution system along with uncertain load conditions under reliability criteria and to develop a methodology to evaluate the reliability of a distribution system integrated with distributed generation. It is proposed to develop a model for distributed generators using wind and solar power generators and compare the developed model with available models. Further, it is possible to optimize the model in terms of siting and sizing of DG and compare the developed model with available models and test its validity.

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