A Critical Review of Distribution Substation System Reliability Evaluations

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ABSTRACT

The significance of a reliable distribution system is hinged on the fact that even if the generation and transmission of a power system are highly reliable, an unreliable distribution system will mean that there will be poor supply of energy to the consumers. Therefore, there must be ways of measuring the reliability of power distribution systems according to given standards in order to help inform the system engineers on the causes of interruptions. This will in turn help in proffering methods of accomplishing a more reliable distribution system. There are established basic methods of assessing the reliability of this system and different researchers engage the one best suited for the analysis they intend to carry out. Moreover, going through previous published works on distribution system reliability evaluation, insight is given into why a distribution behaves below standard and how it could be possibly improved. This paper presents an overview of the basic methods used in reliability assessment with the frequently used reliability indices and a critical review of published works by authors in carrying out the reliability evaluation of different power distribution systems based on these various methods.

Keywords: Interruptions, Distribution systems, Reliability assessment, Reliability indices

1 Introduction

Among the basic needs of a modern society which is necessary for a thriving economy and productive social life is electricity. Electricity has become one of the basic needs of a modern society because of all the benefits and advantages it brings with it which often includes better product quality and higher productivity as a result of increased equipment reliability and availability in industries [1]. Societies all around the world are beginning to realize more than ever before their dependency on electricity and as such they are taking seriously the challenge of having uninterrupted supply. Therefore, having an uninterrupted power supply is non-negotiable in many countries. The distribution systems account for up to about 90% of all consumer reliability problems, hence improving distribution reliability is the key to improving consumer reliability [2]. It usually includes 33-kV lines and the transformations involved before it gets to the consumers' meters as 0.415kV. Distribution system, apart from the service mains, is the last in the hierarchy chain of electrical power systems. The study and evaluation of distribution substation system are required in order to improve its reliability level by providing solutions which may include better system configuration so as to meet the demand of consumers for uninterrupted power supply. It is important to also note that as the demand for electricity increases, owing to growth factor especially among residential consumers and expansion of both commercial and industrial companies, weak points tend to arise in the system. The identification of these weak points is usually not done by mere guessing but by carrying out reliability evaluation of the distribution system.

Thence, carrying out reliability evaluation helps to identify the weak points in a system and also serves as a guide to ensure that proper steps are taken if the system is to be upgraded.

Based on the various kinds of consumers being served by a utility, the effect of interruption of power supply tends to differ and so the decision to be made to increase reliability will also vary accordingly. One of the ways to improve the degree of distribution system reliability is for the distribution company to invest more in its capital equipment by designing a network system configured to accommodate alternative power source and more redundant equipments. However, this may mean that the consumers will pay more to enjoy this higher level of reliability [3]. Hence, the decision of the utilities to invest more on their equipments should be backed by the consumers' perceived need for such which helps to avoid having consumers who are unwilling to pay for additional costs whether on the short-term or long-term goal.

2 PRINCIPLES OF RELIABILITY EVALUATION

Reliability of an electric power system is the probability that the power system will continuously deliver electricity to its consumers without compromise on the quality of the power being delivered [4]. It is also simply a means of assessing whether users have electricity when it is needed [5]. Equipment outages and consumer interruptions are the primary focus of distribution reliability. In normal operating conditions, all components in the distribution substation (except standby) are energized and by implication all customers are energized. Scheduled and unscheduled events disrupt normal operating conditions and can lead to outages of the components in the system and interruptions to power supply. The unscheduled events may be as a result of oversights during installation or maintenance operations, component failures and faults. The scheduled events are usually as a result of the need to carry out maintenance operations on the equipment, construction, consumer request, and usually consumers do get notice of interruption of supply in advance. In addition, the three major factors that affect the reliability of power distribution system are capacity shortages, faults and failures. Capacity shortage can be as a result of inability to meet consumers' demands or inadequate planning to provide redundant element to ensure supply of power in case of unforeseen events. For instance, when there is not enough capacity in the transmission or distribution system to ensure transfer of available electricity within the power system this will mean that some consumers will experience interruptions in the form of load shedding by the utility.

Faults occur when there is short circuit between phases, or phase to ground faults leading to unintended opening of fuses or circuit breakers used for protection within a power distribution system. A fault means that an accidental electrical connection is made between an energized component and something at a different potential leading to a short circuit [6]. The failure of an electrical component is usually not influenced by external factors that may give rise to faults. Failures can be as a result of human error or due to malfunctioning of the equipment. There are several types of failure in electrical equipments and the common types that lead to short circuits include transformer windings, lightning arrestors, and high voltage bushings. Both faults and failures can cause outages which could last for few seconds if it is resolved quickly by operating programmed switching equipment. When an electrical component such as a transformer is damaged due to faults or failures, its replacement or repair usually takes time, sometimes hours or days and as such may lead to longer hours of service interruption to the consumers. In most cases, faults and failures rather than capacity deficiencies are the causes of most outages in a power system. And according to [20], it is not just component outages that affect distribution substation reliability but the time it takes to restore the components back to service.

The reliability of a distribution system is generally divided into system adequacy and system security. The term system adequacy simply refers to a static situation. It checks the capacity of the system to adequately deliver the energy demanded by the customers by carrying out evaluation based on the components or equipment being used. It simply implies that system adequacy focuses on the system design and structure and its installed component capacity [5], [7]. System security is the ability of the system to respond to any given contingency or disturbances such as faults [7]. Therefore, the reliability that concentrates on the system security is called dynamic reliability, while the reliability that focuses on the system adequacy is defined as static reliability.

3. METHODS USED IN RELIABILITY ASSESSMENT

According to [8], the methods applied in carrying out the reliability assessment of a distribution systems are mainly, Analytical Methods based on solution of mathematical models and Simulation Method based on inferences from statistical distributions.

3.1 The Analytical Approach

This approach uses statistical distributions of failure rates of components and their repair times to assess the system's reliability. Failure mode analysis and or minimum cut-set analysis are most commonly used technique for evaluation in analytical method. This method does not adequately represent repair times but has the advantage of requiring less time for computation compared to simulation method. Analytical method is further divided up into Network Modelling and Markov Modelling.

3.1.1 Network Technique

An electrical system can be viewed as a network of its components connected together either in series, parallel, meshed or a combination of these. The structural relationships between a system and its components are considered in this technique. Modeling the failure behavior of the system is one of the major challenges in reliability analysis. However, according to [2], analytical techniques of electrical networks and distribution systems with the generation sources overlooked are mainly based on a failure modes and effects analysis (FMEA), using minimal cuts sets and equations for computing the reliability indices of parallel and series systems. By carrying out analysis on all the components that make up the system, this approach presents all the imminent failure modes and then pin-points their resulting effects on the system. This method determines at least those components within a system which result in an interruption of service at the load-point of interest.

3.1.2 Markov Modeling

Stochastic modeling in reliability engineering is used to explain the functioning of a system with time. In most cases, the component failure and repair times are used as the random variables. A Markov model looks into the present event to determine the future event and does not consider the past event. In other words, the Markov model works solely on the assumption that a system behavior in each state is memoryless. It therefore does not consider the process or event that led to the present event. However, it is possible to generate a stochastic system that is related and similar to the original system or event. This technique requires a large number of states to generate the system to be modeled. This is because as the number of factors/parameters increases, there is a corresponding exponential increase in the number of states. Hence, various assumptions must be made to ensure a controllable sized model.

3.2 Simulation Technique

The behavior of a particular system could follow a random nature. Simulation in reliability analysis often concerns random events and are commonly referred to as Monte Carlo simulations. Simulation can be done using a sequential method in which events are chosen in a given order or random method in which events are chosen at random. In simulation, one of the aims is to make estimates of unknown parameters which will serve as real experiments after observing a simulation process for a specific period. The simulation process is intended for examining and predicting the stochastic behavior of a system in simulated time. This technique takes time and it is expensive to implement because of the need to use huge number of failures to simulate. The fault contribution from each component is given by a statistical distribution of failure rates and outage times. In simulation process, a number of runs are normally performed by the software so as to find the estimates of the means of the output parameters needed such as failure rate, mean repair time, and availability. This is usually done to have a converging result since simulation generates variable outcomes [9] [10].

In a modeled system in which the events in the previous interval directly impact on the next interval, which is often the case in distribution system reliability studies where the action or inaction of one component may affect the performance of the other, then the sequential method is appropriate. In this method, events are set to occur at random times to obey specific probability distributions. The actual behavior of the system is represented by the distribution function gotten from the conversion of the random numbers used. The time-sequential simulation process can also be used to examine and predict behavior patterns in simulated time. This method is an extension of the sequential method, only that, it uses an artificial history of up and down times of the system and it is included in the generation of the random chronological numbers as in sequential simulation. The relationship that exists between the element states and system states serves as template to generate the component histories which help in formulating the sequence of in-service and out-of-service cycles of the system [11].

4 RELIABILITY INDICES

Reliability indices are numerical parameters that reflect the capability of the system to provide its customers an acceptable level of supply [10]. By providing quantitative measures at different individual load points and for the whole system, these indices approximate system reliability. The most important of all the indices used in evaluation of power systems reliability are the duration of interruption and frequency of interruption. This is basically due to the fact that they indicate the expected frequency and the expected duration of interruption of power supply. The frequently used reliability indices for evaluation of systems include: System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI), Average Service Unavailability Index (ASUI), Average Energy Not Served (AENS), System Expected Interruption Cost Index (ECOST), and Energy demanded but not supplied (EDNS). Failure rate, annual unavailability, and average outage duration are the basic indices associated with system load points. By collecting information on the past performance of a system, valuable insight is provided into the reliability profile of the existing system.

5 REVIEW OF DISTRIBUTION SYTEM RELIABILITY EVALUATION

Reference [12] carried out reliability assessment of power distribution system in Nigeria using Ekpoma network, Edo, as a case study. Outage data were collected for January 2012 to December 2012 and the average availability using basic reliability indices was evaluated for Iruekpen, Irrua, and Express feeders which are distribution feeders in Ekpoma. The reliability indices used include: Mean Time Between Failure (MTBF), Mean Down Time (MDT), and Availability. Customer-based indices used include: Customer’s Average Interruption Duration Index (CAIDI), System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Average Service Availability Index (ASAI) and the Average Service Unavailability Index (ASUI). The outages were classified based on type, frequency and durations and the result calculated showed that outages occur in the distribution feeders daily. Earth fault, supply failure, planned outage for maintenance, and load shedding were identified to be the possible causes for interruptions on the feeders. From the study, load shedding was the major reason for interruptions. The study further showed that heat during the dry season and windstorms in the rainy season were factors that could increase the failure rate of the feeders. The authors identified load shedding as the main cause of outages for the feeders analyzed. Planned outages due to maintenance work, supply failures and earth faults were also identified as causes for interruptions on the distribution feeders. The authors made case for improvement of the reliability of the distribution but did not give any recommendations that can bring about this improvement. There were no interpretations for the values of the customer orientation indices computed with reference to reliability benchmark. However, the system has an ASAI value of 0.6147 which means the reliability is very low.

The paper presented by [13] investigated and discussed the faults that impact a typical 11-kV feeder in the Southern part of Kaduna city. There are four outgoing feeders from the 30-MVA, 33/11-kV Peugeot injection substation and Coca-Cola feeder is one of them. The reliability of the case study, 11-kV Coca Cola feeder, was assessed by analyzing the data gotten from the Power Holding Company (PHCN). The data collected was for January 2004 to December 2004 and it contains the type of fault, monthly peak load demand, outage duration, and power losses due to the outages on the feeder. The faults identified were earth fault and overcurrent faults. The earth fault however, contributes more to outages than overcurrent fault and its occurrence is higher during the rainy season than in the dry season. Hence, it was shown that the seasons of the year really affect the integrity of the substation. Amongst the many recommendations given in order to improve the substation's reliability is that the configuration of the distribution system should be redesigned to include ring system which means the consumers will now be supplied by two feeders. This thus removes dependency on just a single feeder. Also, iron cross arms should be used in place of wooden cross arms in order to reduce avoidable earth faults due to broken wooden cross arms. The paper only looked at the feeder distribution system and hence faults and failures that arise from the downstream of the secondary distribution were neglected.

The reliability of secondary distribution substation is significantly affected by outages as a result of faults. According to [14], animals come second to trees as causes of fault which lead to outages in overhead distributions. For instance, short circuit as a result of animals such as lizards and rats entering the control panels, leads to overcurrent faults. In their paper, Min Gui et al. [15], suggested a model for computing the weekly animal-related outages which will help utilities to monitor its performance trends from year to year. By combining wavelet transform techniques and the outputs of neural networks in their work, the models that can estimate weekly animal-caused outages were presented. In most cases, neural networks have overtraining problem and this was overcome by introducing a hybrid approach that integrates Artificial Immune System (AIS). The AIS was used for hypermutation and re-training of the networks and it's an emerging field of computational intelligence. The performance of the model was improved by this hybrid approach while positing that the accuracy of the models can be increased by spatial aggregation. This paper is essentially useful in helping to track the impact of animal-related outages. It however does not provide ways to minimize outages by animals.

As a result of their exposure to the atmosphere, the performance of overhead lines in a distribution system is drastically affected by weather. Line faults can be due to lightning, wind, and other weather factors. Also, frequent interruptions can be as a result of tree branches coming in contact with the lines. Therefore, reducing these forms of interruptions will improve the reliability of the distribution system. In their paper Shalini Gupta et. al. [16], failure rates of overhead lines due to selected set of inputs were predicted using an adaptive fuzzy model. The paper presents an adaptive fuzzy modelling methodology to calculate the effects of wind, lightning, tree trimming and tree density on distribution lines. In order to train the system, data for a period of seven years were obtained from an existing utility. The information included in the data include: type of interruption, date of failure, possible cause and location of failure, number of consumers interrupted, number of feeders, duration of sustained interruption, and protective devices used in clearing faults. This model used the field observations of the selected inputs for few feeders and the resulting numbers of failures as a result of these inputs were recorded. The selected inputs were wind index, lightning, tree density and tree trimming while the output was failure rate. The operation of the model was checked by observing the absolute average error and root mean square. The effectiveness of the trained model was evaluated by carrying out sensitivity analysis. The major problem with this methodology is the large size and quality of data needed. However, with the use of outage management systems (OMS) and geographical information systems (GIS) utilities can provide the data needed.

By using NEPLAN simulation software, a software tool that helps in assessing the configurations of power system, in the paper by [10] a method is presented for evaluation and prediction of distribution system reliability using Choba in Rivers state as case study. NEPLAN Power system software was used to perform an offline simulation of the distribution network considering outage time, incoming energy, outgoing voltages (kV) rating and three-phase current rating. The data for a period of six months was obtained from the Choba Injection substation and used to compute the reliability indices of the distribution system. Customers Average Interruption Duration Index (CAIDI), System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Frequency Index (CAIFI), Customer Interruptions per Interruption Index (CIII), Momentary Average Interruption Frequency Index (MAIFI) and Average Service Availability Index (ASAI) were used in estimating the reliability of the system. The result of the computed reliability indices showed that the distribution system averaged an availability of 99.98% which the authors described as being very poor due to the fact that other utilities have set an ASAI goal of 99.99%. It was recommended that the utility company should be keeping detailed account of data and records which contains component outage time, component failure rate and total energy consumed which will help compute reliability indices such as Energy Demanded Not Supplied.

Most distribution systems are affected by outages which could be as a result of weather, vegetation and animals. Furthermore, it is quite impossible for utilities to completely shield its equipment from these factors. The paper [17] presents a reliability evaluation of outage data obtained from utilities in Kano Distribution Company of Power Holding Company of Nigeria PLC (PHCN). Emphasis of the study was on 33-kV feeder distribution system which included overhead distribution network and underground network systems. The authors carried out a study, thorough analysis on the causes of outages in order to study the pattern in the outages and determine the most significant cause of outage. Exactly 36 stations/service areas in Kano metropolis and the year 2011 and 2012 as base years were used for this evaluation. The reliability indices used in this study include: System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI) and Average Service Availability Index (ASAI). The authors noted that large number of outages was reported in the data as unknown or other causes due to the inexperience of the utility workers. This means a larger number of the outages could not be assigned to a particular cause and this will impact the result gotten by the study. It is therefore important that workers should be trained to be able to identify the causes of outages as this will aid the better and accurate data collection by utilities. More so, the authors suggested that there should be standard way of reporting outages in utilities. The study shows that environmental factors contributed to more than 50% of the outage in the distribution system. The other causes are earth faults, maintenance, unknown and operation. Based on the content of the paper, the justification for the conclusion was not found or included in the paper.

Reference [18] assessed and quantified the reliability performance of Abakpa distribution substation of Kaduna Disco. In addition, the author suggested ways of achieving better reliability performance. The distribution network was assessed with filed data collected from the substation's logbooks for a period of three years, 2010-2012. The substation's failure rate, outage rate, and repair rate were computed by using the duration and frequency of outages in the data. The following reliability indices were also computed: Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), Mean Time To Failure (MTTF), Availability and Reliability. The load outages and downtimes for each year were summed up for each year in order to avoid working with cumbersome data due to the large data involved. It is important to note that the Abakpa substation is a 132-kV/33-kV/11-kV transmission and distribution substation. The cumulative fault frequency, period of occurrence and total downtime for each year were computed and used to calculate the reliability indices mentioned earlier. The reliability indices were computed for components and for nature/causes of failure for each of the year understudied. Examples of the component faults include: earth leakage fault, switch gear related fault, fault tripping fault, faulty transformers, tree falling on line, failure on line due to jumpers, reactor faults, overcurrent etc. The result showed that contrary to one of the objectives of the paper, the author failed to suggest a distribution network design that will improve the reliability of the substation while it mentioned that simple overhead radial systems have poor reliability performance. The paper, however, discussed some of the factors that influence reliability such as vegetation, animals, and environmental factors. Circuit length was also pointed out as a factor that affects reliability as longer circuits are susceptible to interruptions.

According to [7], reliability can be increased by increased investment bringing about a decrease in the utility outage cost of the system. This outage cost can usually be computed by multiplying the energy cut to the consumer by the cost of the kWh not supplied. By employing analytical technique, the study carried out by [19] assessed the reliability of Onitsha Business Unit within the period of three years, 2009 to 2011. This technique requires the use of outage data which was obtained from the Power Holding Company (PHCN) for the various feeders in the Onitsha distribution system. The paper also presented the impact of having photovoltaic (PV)/inverter interconnected with the network in order to improve the reliability of the system. The authors investigated the factors causing poor reliability performance, and possible ways to bring about improvements to the system. In the paper, the system reliability indices computed include: Average Failure Rate at Load point, Annual outage duration at Load Point, Average outage Duration at Load Point, System Expected Energy Not Supplied (EENS), System Expected Interruption Cost Index (ECOST), Interrupted Energy Assessment Rate Index at Load Point (IEARN), Average Energy Not Supplied Index (AENS), System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI), and Average Service unavailability Index (ASUI). To analyze the effect of improving the reliability of the system by having alternative or complementary source (PV/inverter) interconnected at the 11-kV busbar, ETAP software was used. The algorithm used in the software was displayed and the simulation was carried out with a set-up having a self-driven fixed frequency inverter design connected to 11-kV distribution bus to supply the loads whenever there is outage in the utility. The results obtained showed 61.2%, 55.7% and 65.1% reductions in revenue loss for 2009, 2010, and

2011 respectively after the PV installation. The cause of the substation's poor performance was not discussed in the paper though it was stated as part of the objectives. However, this paper has shown that reliability performance can be improved upon by introducing a complementary source and that by effectively utilizing solar technologies such as PV, there will be less erratic supply of power to consumers.

6 Conclusion

Although a The reliability of distribution system directly affects the consumers, hence different works and researches have shown the causes of interruptions and how they can be effectively managed in order to improve the supply of electricity to consumers. Utilities are better informed in making decision to improve reliability with the help of reliability evaluation. Therefore, irrespective of the methods employed to assess a distribution substation system, the most important thing is to interpret the results according to standard and give possible recommendations that can fast track this improvement.

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