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OUTLINE OF THE BOOK

1.1 INTRODUCTION

Reliability is an abstract term meaning endurance, dependability, and good performance. For engineering systems, however, it is more than an abstract term; it is something that can be computed, measured, evaluated, planned, and designed into a piece of equipment or a system. Reliability means the ability of a system to perform the function it is designed for under the operating conditions encountered during its projected lifetime.

Historically, a power system has been divided into three almost independent areas of operation as follows:

1. *Generation System*: facilities for the generation of electricity from economical energy sources.
2. *Transmission System*: transportation system to move large energy blocks from generation facilities to specific geographical areas.
3. *Distribution System*: within a specific geographical area distribute the energy to individual consumers (e.g., residential, commercial, industrial, etc.).

Power Distribution System Reliability. By Ali A. Chowdhury and Don O. Koval

Ideally, a power system's reliability from the viewpoint of consumers means uninterrupted supply of power from the generation, transmission, or distribution systems. In reality, the key indicators of a power system's reliability for consumers are the frequency and duration of interruptions at their point of utilization (i.e., their load point). From an engineering viewpoint, the question is how do you determine mathematically the frequency and duration of load point interruptions? The "how to, assessment for distribution systems with practical examples is the subject of this book.

1.2 RELIABILITY ASSESSMENT OF POWER SYSTEMS

The basic function of a power system is to supply its customers with electrical energy as economically and as reliably as possible. There were some simple applications of probability methods to calculations of generation reserve capacity since 1940s; however, the real interest in power system reliability evaluation started to take off only after 1965, most notably influenced by the New York City blackout that year. Reliability mathematics is constantly evolving to accommodate technical changes in operations and configurations of power systems. At present, renewable energy sources such as wind and photovoltaic systems have a significant impact on the operation of generation, transmission, and distribution systems.

At present, deregulation is forcing electric utilities into uncharted waters. For the first time, the customer is looking for value-added services from their utilities or they will start shopping around. Failure to recognize customer needs has caused a great number of business failures in numerous industries. The electric industries' movement toward a competitive market forces all related businesses to assess their focus, strengths, weaknesses, and strategies. One of the major challenges to electric utilities is to increase the market value of the services they provide with the right amount of reliability and to lower their costs of operation, maintenance, and construction to provide customers electricity at lower rates. For any power system supplying a specific mix of customers, there is an optimum value of reliability that would result in lowest combined costs. Quantitative value-based reliability planning concepts presented in this book are an attempt to achieve this optimum reliability in power systems.

1.2.1 Generation System Reliability Assessment

In evaluating generation capacity adequacy, the commonly accepted definition of failure is "loss of load„ which is an outage due to capacity inadequacy. The reliability is defined in terms of the loss of load probability in a given time interval, usually a year, or the loss of load expectation (LOLE) in days per year. For a loss of load to occur, the system capacity has to fall to a level due to scheduled maintenance and/or forced outages of other generating units by a margin exceeding the spinning reserve to meet the system peak load. Even then, there may not be an outage because the system load is not always at its peak. To calculate the amount of time when the capacity cannot meet the actual load of the time, the load duration curve has to be brought into the picture. The most commonly used generation reliability index of LOLE can be calculated if all parameters, namely, forced outage rates of different generating units, the load forecast, the load duration curve, the spinning reserve, and the other refinements deemed necessary (e.g., reliability of the transmission system), are known. Significant research has gone into developing reliability assessment tools and models applied to generating capacity adequacy over the past four decades. Electric utilities are routinely performing probabilistic assessments of generation reserve margin requirements using the sophisticated tools based on *Monte Carlo simulation* and *contingency enumeration* approaches. Recent developments in generating capacity adequacy assessment include, but are not confined to, novel models for energy limited units such as wind, solar, geothermal, and other exotic energy technologies and merchant plant modeling as well as capacity market design models for deregulated markets. The system planning engineer can then decide if the level of reliability is adequate and also determine the effect of alternative actions such as increasing the spinning reserve, adding a generating unit, and changing the maintenance schedules and interconnections with other areas.

1.2.2 Transmission System Reliability Assessment

In earlier reliability works on generation capacity adequacy assessments, only the energy production systems were considered. The transmission and distribution systems were ignored. In a mathematical sense, the transmission and distribution systems were implicitly assumed to be perfectly reliable, which in reality was not true. Determining the probability of system capacity outage levels based on the forced outage rates of the generators alone will lead to overly optimistic results.

The transmission system consists of high-voltage transmission lines and terminal stations including different equipment and control. The average forced failure rate and outage duration of each component such as line sections, transformers, and circuit breakers of the transmission system can be computed and the reliability of a load point can be calculated using an appropriate reliability model.

The load point reliability depends on the reliability of the individual component; however, it also depends on other factors. The two most important factors are system configuration and environment. The transmission system is a network of lines and equipment. Failure of one component does not necessarily render the system failure. There is a lot of inherent redundancy in other parts of the transmission system. Another factor in transmission system reliability is the weather and environment under which it is subjected to operate. The failures of many outdoor components are caused by lightning, snow, high winds, and so on. In addition, failures are not always independent as generally assumed in statistical calculations. The failure of one component may increase the chance of failure of another. One type of such dependent failures is the common-mode failure, that is, failure of more than one component due to the same cause, which generally happens more often in inclement weather than in fair weather. In the analysis of transmission system reliability, therefore, different failure rates are assigned to different weather conditions, and the dependency of failures, at least in adverse weather, has to be taken into account. It can be seen that a detailed analysis can be very complex and it gets more complex when the composite generation and transmission system is taken together. The use of powerful computers is almost mandatory for any system reliability analysis. Significant works have been done in probabilistic assessments of transmission systems to augment the current deterministic criteria in planning and designing of transmission systems.

1.2.3 Distribution System Reliability Assessment

The application of reliability concepts to distribution systems differs from generation and transmission applications in that it is more customer load point oriented instead of being system oriented, and the local distribution system is considered rather than the whole integrated system involving the generation and transmission facilities. Generation and transmission reliability also emphasizes capacity and loss of load probability, with some attention paid to components, whereas distribution reliability looks at all facets of engineering: design, planning, and operations. Because the distribution system is less complex than the integrated generation and transmission system, the probability mathematics involved is much simpler than that required for generation and transmission reliability assessments.

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.

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.

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. Unlike bulk transmission system that is subject to North American Electric Reliability Council's deterministic criteria in planning and designing the transmission systems, the distribution system is not subject to any established planning standards. Distribution utilities are required only to furnish historical distribution system performance indices to regulatory agencies.

There are ample opportunities for distribution utilities to judiciously invest in distribution system expansion activities to meet the future load growth by using the probabilistic reliability methods that would eliminate the risk of over/underinvestment in the system while providing the optimum service reliability at the right cost. The reluctance of electric utilities to use the reliability methods in planning and designing distribution systems is due to the prevailing perception that it requires sophisticated probabilistic computer tools and trained engineers in power system reliability engineering. This book intends to eliminate this misperception and presents practical probabilistic reliability models for planning and designing distribution systems.

The applications of the developed reliability models presented in this book are illustrated using hand calculations that require no sophisticated computer tools and virtually little or no knowledge of probability mathematics. Problem sets and answers are provided at the end of the book to test the reader's ability to solve reliability problems in distribution systems.

1.3 ORGANIZATION OF THE CHAPTERS

Two approaches to reliability evaluation of distribution systems are normally used, namely, historical assessment and predictive assessment. Historical assessment involves the collection and analysis of distribution system outage and customer interruption data. It is essential for electric utilities to measure actual distribution system reliability performance levels and define performance indicators to assess the basic function of providing cost-effective and reliable power supply to all customer types. Historical assessment generally is described as measuring the past performance of a system by consistently logging the frequency, duration, and causes of system component failures and customer interruptions. Predictive reliability assessment, however, combines historical component outage data and mathematical models to estimate the performance of designated configurations. Predictive techniques therefore rely on two basic types of data to compute service reliability: component reliability parameters and network physical configurations.

This book deals with both historical and predictive distribution system reliability assessments. Simple and easy-to-use practical reliability models have been developed and their applications illustrated using practical distribution system networks. Virtually all reliability calculations have been performed by hand and no sophisticated computer programs are necessary. A simple but realistic live distribution system has been frequently used to illustrate the application of different reliability models developed and presented in this book. For the convenience of the readers, the mathematical reliability models and formulas relevant to particular applications have been repeated in chapters where necessary to maintain the flow of understanding the models and concepts. Each chapter is independent of other chapters, and cross-referencing different chapters is not required to understand the new concepts presented in a particular chapter. The applications of the novel concept of reliability cost–reliability worth or commonly known as the value-based reliability model are extensively discussed and illustrated with many numerical examples in this book.

The book is organized as follows:

Chapter 1 presents the basic definition of the term ‘‘reliability, and its application to power systems. The current state of the reliability methodology applications in generation, transmission, and distribution segments of the power system is briefly described.

Chapters 2 and 3 very briefly describe fundamentals of probability theories and reliability principles. Although the basic probability and reliability models presented with numerical examples in Chapters 2 and 3 are available in many textbooks, these models are repeated in these chapters to help the readers understand the models that will be used extensively in the later chapters of this book. The majority of systems in the real world do not have a simple structure or are operated by complex operational logic. For solving complex networks or systems, additional modeling and evaluation techniques are required to evaluate the reliability of such networks or systems. Chapters 2 and 3 also include models to assess the reliability complex network configurations. The basic models for complex network solutions have been illustrated using numerical examples.

Chapter 4 illustrates the applications of the probability and statistical models presented in Chapters 2 and 3 using simple numerical examples in distribution system planning and designing. Distribution system planners will be able to utilize the probability and statistical models by using hand calculations in real-life situations.

Chapter 5 presents the basic engineering economics models. The economics concepts and models related to distribution system planning and design are illustrated with numerous simple examples. The novel value-based reliability model presented in later chapters is based on economic theories discussed in Chapter 5.

In Chapter 6, the basic models for complex network solutions are illustrated using numerous numerical examples. Chapter 6 introduces models to assess the reliability complex network configurations. Some of the common methodologies in practice are (1) state enumeration methods (event-space methods), (2) network reduction methods, and (3) path enumeration methods.

In Chapter 7, a description is given of how to make quantitative reliability and availability predictions for proposed new configurations of industrial and commercial power distribution systems. Several examples are worked out, including a simple radial system, a primary selective system, and a secondary selective system. The simple radial system that was analyzed had an average number of forced hours of downtime per year that was 19 times larger than a secondary selective system; the failure rate was 6 times larger. The importance of two separate power supply sources from the electric utility provider has been identified and analyzed. This approach could be used to assist in cost–reliability trade-off decisions in the design of power distribution systems.

Chapter 8 presents a zone branch methodology that overcomes many of these limitations and applies the methodology to a large industrial plant power system configuration. There are many methods available for evaluating the frequency and duration of load point interruptions within a given industrial power system configuration. However, as systems become larger and more interconnected, these existing methods can become computationally bound and limited in their ability to assess the impact of unreliable protective equipment and unreliable protection coordination schemes on individual load point reliability indices within a given plant configuration. These methods also may not often account for complex isolation and restoration procedures within an industrial plant configuration that are included in the zone branch reliability methodology.

Chapter 9 deals with the types of data needed for distribution system's predictive reliability assessments and presents typical distribution component outage statistics in urban and rural environments for use in predictive reliability analysis. This database is the result of comprehensive synthesis of a large number of industry data available in different technical publications. The distribution system is an important part of the total electric supply system as it provides the final link between a utility's bulk transmission system and its ultimate customers. All quantitative reliability assessments require numerical data. Historical assessment generally analyzes discrete interruption events occurring at specific locations over specific time periods. Predictive assessment determines the long-term behavior of systems by combining component failure rates and the duration of repair, restoration, switching, and isolation activities for the electric utility's distribution system for given system configurations to calculate average reliability performance. Accurate component outage data are therefore the key to distribution system predictive performance analysis. In addition to the physical configuration of the distribution network, the reliability characteristics of system components, the operation of protection equipment, and the availability of alternative supplies with adequate capacity also have a significant impact on service reliability.

In Chapter 10, the methodology used to assess the historical reliability performance of a practical utility's electric distribution system is outlined. Included in the discussion is an overview of the process used to collect and organize the required interruption data as well as a description of the performance indices calculated for use in the causal assessment. Various components of reliability performance assessment are described, including reliability indices, comparison between years of operation, comparisons of the averages at different levels of the system, and outage cause and component failures. The application of the calculated performance statistics in planning, operating, and maintaining distribution systems is also described.

Chapter 11 provides a brief overview of current deterministic planning practices in utility distribution system planning and design. The chapter also introduces a probabilistic customer value-based approach to alternative feed requirements planning for overhead distribution networks to illustrate the advantages of probabilistic planning.

Chapter 12 identifies a number of pertinent factors and issues taken into account in establishing distribution reliability standards and illustrates the issues and factors considered in using historical reliability performance data. Actual utility data are used in the illustrations. The development of standard distribution reliability metric values, for example, System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI), against which all utilities can compare performance, can be problematic without strict adherence to a national or international standard (e.g., IEEE Standard 1366). This issue has been discussed in Chapter 11. At present, there are many differences between data collection processes and characteristics of utility systems to make comparisons against such standard metric values impossible for many utilities. Rather, the development of uniform standard metric values, which utilities compare to their own historical reliability performance indices, is more practical. If cross-comparisons between utilities are desirable, a number of issues and factors associated with individual utilities must be taken into consideration when establishing distribution reliability standards.

Chapter 13 identifies a number of factors and issues that should be considered in generating a PBR (performance-based rate making) plan for a distribution utility. A brief analysis of cause contributions to reliability indices is also performed and presented in this chapter. The historic reliability-based PBR framework developed in this chapter will find practical applications in the emerging deregulated electricity market. In an attempt to reregulate the distribution segment of an electric power system, public utility commissions (PUCs) in a number of states in the United States are increasingly adopting a reward/penalty framework to guarantee acceptable electric supply reliability. This reward/penalty framework is commonly known as PBR. A PBR framework is introduced to provide distribution utilities with incentives for economic efficiency gains in the competitive generation and transmission markets. A distribution utility's historical reliability performance records could be used to create practical PBR mechanisms. The chapter presents actual reliability performance history from two different utilities to develop PBR frameworks for use in a reregulated environment. An analysis of financial risk related to historic reliability data is presented by including reliability index probability distributions in a PBR plan.

Chapter 14 presents the basic concepts and applications for computing load point customer reliability indices and interruption costs. Case studies showing the applications of load point reliability index calculations including customer interruption costs in distribution system planning are described in detail. The practical distribution system used in this chapter to illustrate the computation of the load point customer interruptions costs has been extensively applied in Chapters 15, 16 and 19 for demonstrating value-based predictive system planning methods, probabilistic distribution network isolation, and restoration procedures and for determining distributed generation (DG) equivalence to replace a distribution feeder requirement.

Chapter 15 presents a series of case studies of an actual industrial load area supplied by two feeder circuits originating from two alternate substations. A basic conclusion of this chapter is that expansion plans of an industrial distribution system can be optimized in terms of reliability by using an economic criterion in which the sum of both the industrial facility interruptions and the utility system costs is minimized. Society is becoming increasingly dependent on a cost-effective reliable electric power supply. Unreliable electric power supplies can be extremely costly to electric utilities and their customers. Predictive reliability assessment combines historical outage data and mathematical models to estimate the performance of specific network and system configurations. Chapter 15 has expanded the customer interruption cost methodology presented in Chapter 14 and applied to a practical distribution in illustrating the value-based assessment of proposed modifications to an existing industrial distribution system configuration to minimize the costs of interruptions to both the utility and the utility's industrial customers.

Chapter 16 presents a new restoration methodology for distribution system configurations that maximizes the amount of load that can be restored after a grid blackout, substation outage, and distribution feeder line section outages and evaluates the cost of load point interruptions considering feeder islanding and substation capacity constraints. Several case studies with restoration tables have been presented and discussed to clearly reveal the impact of distribution system capacity constraints on load point reliability indices and the cost of load point interruptions. A recent report on the U.S.–Canada blackout on August 14, 2003 revealed that the duration of restoring the Eastern Interconnect to a normal operating configuration was lengthy and complicated. One of the difficulties in modeling a power system is to represent the significant changes in loading patterns that present themselves during the restoration process after a major outage. The capacity of the equipment may be adequate during normal operating conditions; however, it may be severely compromised during restoration procedures, particularly the restoration of thousands of distribution system feeder circuits.

Chapter 17 presents a customer cost–benefit probabilistic approach to designing meshed urban distribution systems. The customer value-based reliability methodology is illustrated using a practical urban distribution system of a Canadian utility. Achieving high distribution reliability levels and concurrently minimizing capital costs can be viewed as a problem of optimization. Using mathematical models and simulations, a comparison of design concepts can be performed to compute the optimal feeder section length, feeder loading level, and distribution substation transformer loading level. The number of feeder ties and feeder tie placement in a meshed network are also optimized through the models. The overall outcome of this analysis is that capital costs can then be directed toward system improvements that will be most cost-effective in improving distribution system reliability.

Chapter 18 discusses a reliability methodology to improve the radial distribution feeder reliability performance normally prevailing in a rural environment using a simple illustrative feeder configuration. As indicated earlier, historical distribution feeder reliability assessment generally summarizes discrete interruption events occurring at specific locations over specific time periods, whereas predictive assessment estimates the long-term behavior of systems by combining component failure rates and repair (restoration) times that describe the central tendency of an entire distribution of possible values with feeder configurations. The outage time due to component failures can substantially be reduced by protection and sectionalizing schemes. The time required to isolate a faulted component by isolation and switching action is known as switching or restoration time. The provision of alternative supply in radial networks normally enhances the load point reliability. Fuses usually protect the lateral distributors connected to the customers.

Chapter 19 delves into a reliability model for determining the DG equivalence to a distribution facility for use in distribution system planning studies in the new competitive environment. The primary objective of any electric utility company in the new competitive environment is to increase the market value of the services by providing the right amount of reliability and, at the same time, lower its costs of operation, maintenance, and construction of new facilities to provide customers its services at lower rates. The electric utility company will strive to achieve this objective by many means, one of which is to defer the capital distribution facility requirements in favor of a DG solution by an independent power producer (IPP) to meet the growing customer load demand. In this case, the distribution capital investment deferral credit received by the IPP will depend on the incremental system reliability improvement rendered by the DG solution. In other words, the size, location, and reliability of the DG will be based on the comparable incremental reliability provided by the distribution solution under considerations.

Chapter 20 discusses probabilistic models developed based on Poisson probability distribution for determining the optimal number of transformer spares for distribution transformer systems. To maintain adequate service reliability, a distribution utility needs to maintain a certain number of distribution equipment in its inventory as spare equipment. The outage of a transformer is a random event, and the probability mathematics can best describe this type of failure process. The developed models have been described by using illustrative 72 kV distribution transformer systems. Industry average catastrophic transformer failure rate and a 1-year transformer repair or procurement time have been used in examples considered in the chapter. Among the models developed for determining the optimum number of transformer spares, the statistical economics model provides the best result as it attempts to minimize the total system cost including the cost of spares carried in the system.

Chapter 21 deals with service quality issues in terms of voltage sags and surges. A voltage sag may be caused by a switching operation involving heavy currents or by the operation of protective devices (including autoreclosers) resulting from faults. These events may emanate from the consumer's systems or from the public supply network. Voltage sags and short supply interruptions may disturb the equipment connected to the supply network and cause a consumer interruption. The conclusions of this chapter are that some of the inconveniences created by power quality problems are made worse by the fact that restarting an industrial process may take from a few minutes to a few hours. This chapter attempts to answer many questions asked by a utility's industrial customers. The answers presented in Chapter 21 are based on the statistical characteristics of the Canadian National Power Quality Survey.

1.4 CONCLUSIONS

This chapter has introduced the basic definition of the term "reliability, in a more generic form. The application of reliability techniques to power systems performance assessment was discussed briefly. Power generation system reliability evaluation by using the reliability techniques using the 1 day in 10 years loss of load expectation criterion is an accepted practice in the electric power industry. Reliability assessments in transmission systems have made great strides in recent years, and sophisticated computer models are available for large-scale transmission system assessments. With the recent movement toward competition in the electric energy market, increasing attention is being paid to the utilization of probabilistic reliability techniques in distribution system assessments and performance-based rate makings. This book is an attempt to achieve the objective of providing distribution planning engineers simple and easy-to-use reliability models that can be applied in routine distribution system cost–benefit enhancement planning without resorting to sophisticated computer tools. The reliability concepts and models developed and illustrated with practical system examples do not require knowledge of probability mathematics, and virtually all reliability assessment tasks can be performed by hand calculations. It is important to note that the book does not purport to cover every known and available method in distribution system reliability planning, as it would require a text of infinite length.

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