PART I

Concepts and Methods in System Reliability

1

Introduction to Reliability

1.1 Introduction

The term reliability is generally used to relate to the ability of a system to perform its intended function. The term is also used in a more definite sense as one of the measures of reliability and indicates the probability of not failing by the end of a certain period of time, called the mission time. In this book, this term will be used in the former sense unless otherwise indicated. In a qualitative sense, planners and designers are always concerned with reliability, but the qualitative sense does not help us understand and make decisions while dealing with complex situations. However, when defined quantitatively it becomes a parameter that can be traded off with other parameters, such as cost and emissions.

There can be many reasons for quantifying reliability. In some situations, we want to know what the reliability level is in quantitative measures. For example, in military or space applications, we want to know what the reliability actually is, as we are risking lives. In commercial applications, reliability has a definite trade-off with cost. So we want to have a decision tool for which reliability needs to be quantified. The following example will illustrate this situation.

Example 1.1 A system has a total load of 500 MW. The following options are available for satisfying this load, which is assumed constant for simplicity:

5 generators, each with 100 MW;
6 generators, each with 100 MW;
12 generators, each with 50 MW.

The question we need to answer in terms of design and operation aspect is: *Which of these alternatives has the best reliability?*

A little thinking will show that there is no way to answer this question without some additional data on the stochastic behavior of these units, which are failure and repair characteristics. After we obtain this data, models can be built

Electric Power Grid Reliability Evaluation: Models and Methods, First Edition. Chanan Singh, Panida Jirutitijaroen, and Joydeep Mitra.

to quantify the reliability for these three cases, and then the question can be answered.

1.2 Quantitative Reliability

Most of the applications of reliability modeling are in the steady state domain or in the sense of an average behavior over a long period of time. If we describe the system behavior at any instance of time by its state, the collection of possible states that the system may assume is called the *state space*, denoted by S.

In reliability analysis, one can classify the system state into two main categories, success or failure states. In success states the system is able to do its intended function, whereas in the failed states it cannot. We are mostly concerned with how the system behaves in failure states. The basic indexes used to characterize this domain are as follows.

Probability of failure

Probability of failure, denoted by p_f, is the steady state probability of the system being in the failed state or unacceptable states. It is also defined as the long run fraction of the time that system spends in the failed state. The probability of system failure is easily found by summing up the probability of failure states as shown in (1.1):

$$p_f = \sum_{i \in Y} p_i, \tag{1.1}$$

where

p_f system unavailability or probability of system failure;
Y set of failure states, $Y \subset S$;
S system state space.

Frequency of failure

Frequency of failure, denoted by f_f, is the expected number of failures per unit time, e.g., per year. This index is found from the expected number of times that the system transits from success states to failure states. As will be seen clearly in Chapter 4, this index can be easily obtained by finding the expected number of transitions across the boundary of subset Y of failure states.

Mean cycle time

Mean cycle time, denoted by T_f, is the average time that the system spends between successive failures and is given by (1.2). This index is simply the reciprocal of the frequency index:

$$T_f = \frac{1}{f_f}. \tag{1.2}$$

Mean down time

Mean down time, denoted by T_D, is the average time spent in the failed states during each system failure event. In other words, this is the expected time of stay in Y in one cycle of system up and down periods. This index can be found from (1.3):

$$T_D = \frac{p_f}{f_f}. \tag{1.3}$$

Mean up time

Mean up time, denoted by T_U, is the mean time that the system stays in the up states before system failure and is given by (1.4):

$$T_U = T_f - T_D. \tag{1.4}$$

There are several other indices that can be obtained as a function of the above indices, and these will be discussed in Chapter 5.

There are also applications in the time domain, say $[0, T]$. For example, at time 0, we may be interested in knowing the probability of not having sufficient generation at time T in helping decide the start of additional generation. The following indices could be used in such situations:

1. Probability of failure at time T
   This indicates the probability of being in the failed state at time T. This does not mean that the system did not fail before time T. The system may have failed before T and repaired, so this only indicates the probability of the system being in a failed state at time T.
2. Reliability for time T
   This is the probability that the system has not failed by time T.
3. Interval frequency over $[0, T]$
   This is the expected number of failures in the interval $[0, T]$.
4. Fractional duration
   This is the average probability of being in the failed state in interval $[0, T]$.

The most commonly computed reliability measures can be categorized as three indices as follows.

1. Expected value indexes: These indices involve
   Expected Power Not Supplied (EPNS) or Expected Unserved Energy (EUE).
2. Probability indices such as
   Loss of Load Probability (LOLP) or Loss of Load Expectation (LOLE).
3. Frequency and duration indices such as
   Loss of Load Frequency (LOLF) or Loss of Load Duration (LOLD).

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1.3 Basic Approaches for Considering Reliability in Decision-Making

Having quantified the attributes of reliability, the next step is to see how it can be included in the decision process. There are perhaps many ways of doing it, but the most commonly used are described in this section. It is important to remember that the purpose of reliability modeling and analysis is not always to achieve higher reliability but to attain the required or optimal reliability.

Reliability as a constraint

Reliability can be considered a constraint within which other parameters can be changed or optimized. Until now this is perhaps the most common manner in which reliability considerations are implemented. For example, in generation reliability there is a widely accepted criterion of loss of load of one day in 10 years.

Reliability as a component of overall cost optimization

The conceptual relationship between cost and reliability can be appreciated from Figure 1.1. The overall cost is a combination of the investment cost and the cost of failures to the customers. The investment cost would tend to increase if we are interested in higher levels of reliability. The cost of failures to the customers, on the other hand, tends to decrease with increased level of reliability. If we combine these costs, the total cost is shown by the solid curve, which has a minimum value. The reliability at this minimum cost may be considered an optimal level; points to the left of this would be dominated by customer dissatisfaction, while points to the right may be dominated by investment cost considerations.

It can be appreciated that in this type of analysis we need to calculate the worth of reliability. In other words, how much do the customers think that

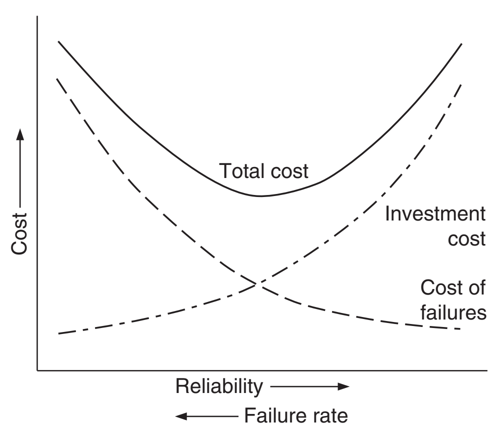

Figure 1.1 Trade-off between reliability and cost.

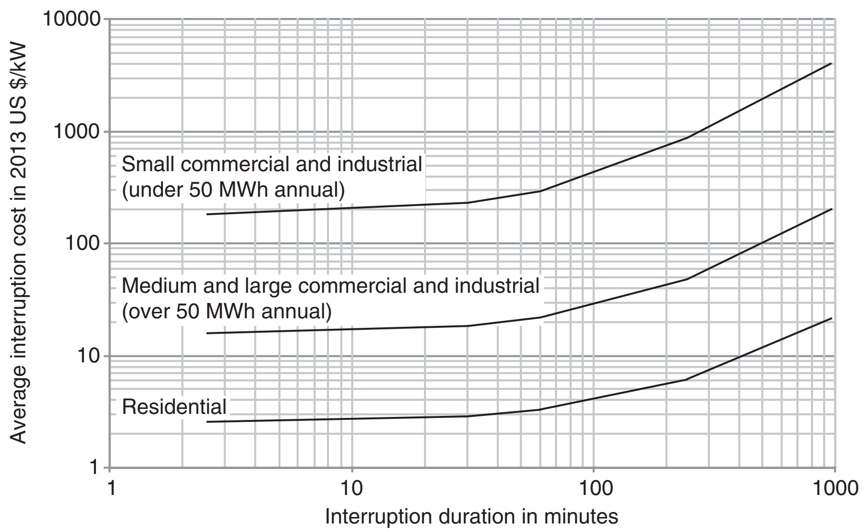

Figure 1.2 Customer damage function (compiled from data in [1]).

interruptions of power cost them? One way of doing this is through customer damage function, like the one shown in Figure 1.2.

The customer damage function provides the relationship between the duration of outage and the interruption cost in \$/kW. The damage function is different depending on the type of customer. The damage function is clearly nonlinear with respect to the duration, increasing at much higher rates for longer outages. The frequency and duration indices defined earlier can be combined to yield the cost of interruptions using (1.5):

$$IC = \sum_{i=1}^{n} L_i f_i c_i(d_i), \tag{1.5}$$

where

n	number of load points in the system;
L_i	load requirement at load point i in kW;
f_i	failure frequency at load point i in number of occurrence per year;
$c_i(d_i)$	customer damage function at load point i in \$ per kW in terms of outage duration d_i;
d_i	outage duration at load point i in hours.

Multi objective optimization and pareto-optimality

Generally there are conflicting objectives to be satisfied or optimized. For example, cost and reliability are conflicting objectives. Multi objective

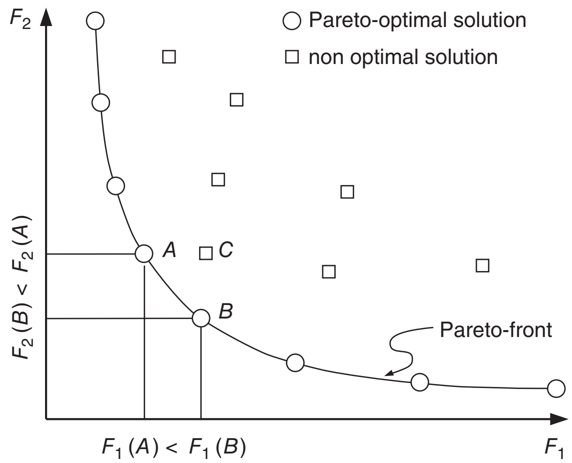

Figure 1.3 Multi objective optimization.

optimization, also known as multi criteria or multi attribute optimization, is the process of simultaneously optimizing two or more conflicting objectives subject to certain constraints. In multi objective optimization, Pareto-optimal solutions are usually derived, where the improvement of an objective will inevitably deteriorate at least another one. An example can be seen in Figure 1.3—given that lower values are preferred to higher values, point *C* is not on the Pareto frontier because it is dominated by both point *A* and point *B*; and points *A* and *B* are non inferior.

1.4 Objective and Scope of This Book

In general, reliability needs to be built, as far as possible, at the design or planning stage of a product or a system. Corrective actions to fix the reliability are generally more inconvenient and expensive. So far as the power grid is concerned, it is emerging as a highly complex system with heavy penetration of renewable energy sources, central and distributed energy storage and massive deployment of distributed communication and computational technologies allowing smarter utilization of resources. In addition, as the shape of the grid unfolds, there will be higher uncertainty in the planning and operation of these systems. As the complexity and uncertainty increase, the potential for possible failures with a significant effect on industrial complexes and society can increase drastically. In these circumstances maintaining the grid reliability and economy will be a very important objective and will be a challenge for those involved. Although many activities are involved in meeting these goals, educating the engineers in the discipline of reliability provides them with tools of analysis, trade-off and mental models for thinking. Reliability cannot be left to the goodwill of those designing or planning systems nor as a byproduct of these processes but must be engineered into the grid and its subsystems in a systematic and deliberate manner. An important step in this process is to model, analyze and predict the effect of design, planning and operating decisions on the reliability of the system. So there is a need for educational tools covering the spectrum of reliability modeling and evaluation tools needed for this emerging complex cyber-physical system.

The objective of this book is to provide state of the art tools for modeling and analyzing this system's reliability. This material will be useful for those who need to use these tools as well as those who want to do further research. They will be able to use this knowledge to make trade-offs between reliability, cost, environmental issues and other factors as needed.

To achieve this objective, we provide a strong background in general reliability that cultivates a deep understanding that can be used to develop appropriate tools as needed. We then use this foundation to build the tools for analyzing the power systems. The book can thus be used both by those who want to understand the tools of reliability analysis and those who want expertise in power system reliability.

1.5 Organization of This Book

We divide this book into two parts to meet its objective. The first part focuses on the basics of probability and stochastic processes as well as methods of reliability analysis developed based on these concepts. This part can be used by those who may be interested in learning about reliability methods in general. The second part develops models and methods that apply specifically to power system reliability.