

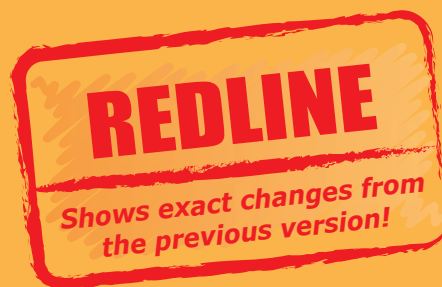
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493™

IEEE Recommended Practice for the

Design of Reliable Industrial and Commercial Power Systems



Published by the
Institute of Electrical and
Electronics Engineers, Inc.

IEEE Std 493™-2007
(Revision of
IEEE Std 493-1997)

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IEEE Std 493™-2007

(Revision of
IEEE Std 493-1997)

IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems

Sponsor

**Power Systems Reliability Subcommittee
of the
Power Systems Engineering Committee
of the
IEEE Industry Applications Society**

Approved 7 February 2007

IEEE-SA Standards Board

Abstract: The fundamentals of reliability analysis as it applies to the planning and design of industrial and commercial electric power distribution systems are presented. Included are basic concepts of reliability analysis by probability methods, fundamentals of power system reliability evaluation, economic evaluation of reliability, cost of power outage data, equipment reliability data, and examples of reliability analysis. Emergency and standby power, electrical preventive maintenance, and evaluating and improving reliability of the existing plant are also addressed. The presentation is self-contained and should enable trade-off studies during the design of industrial and commercial power systems. Design, installation, maintenance practices for electrical power and grounding (including both power-related and signal-related noise control) of sensitive electronic processing equipment used in commercial and industrial applications are presented.

Keywords: designing reliable industrial and commercial power systems, equipment reliability data, industrial and commercial power systems reliability analysis, reliability analysis

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Print: ISBN 0-7381-5300-1 SH95606
PDF: ISBN 0-7381-5301-X SS95606

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Acknowledgments

Grateful acknowledgment is made to the following for having granted permission to reprint material in this document:

Alion Science and Technology, System Acquisition and Supportability Division, Chapter 5.

EYP Mission Critical Facilities, Inc., Chapter 8.

HDR Engineering Inc., Chapter 4.

Don O. Koval, University of Alberta, Chapters 1, 3, and 9.

Pat O'Donnell, Chapter 6.

SoftSwitching Technologies Corporation, Chapter 7.

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Introduction

This introduction is not part of IEEE Std 493-2007, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems.

The objective of this recommended practice is to present the fundamentals of reliability analysis applied to the planning and design of industrial and commercial electric power distribution systems. The intended audience for this material is primarily consulting engineers and plant engineers, and technicians. The design of reliable industrial and commercial power distribution systems is important because of the high cost associated with power outages. It is necessary to consider the cost of power outages when making design decisions for new and existing power distribution systems as well as to have the ability to make quantitative “cost-versus-reliability” trade-off studies. The lack of credible data concerning equipment reliability and the cost of power outages has hindered engineers in making such studies. This revision of IEEE Std 493™ overcomes these obstacles by providing extensive mechanical and electrical equipment reliability data; complete U.S. Army Corp of Engineers Power Reliability Enhancement Program (PREP) database, recent cost of power outage data, data collection procedures for maintenance and equipment failures, 7 × 24 continuous power analysis, and voltage sag analysis are presented. Detailed examples of reliability analysis of various industrial distribution system operating configurations are presented. The authors of this book have attempted to provide sufficient information so that reliability analyses can be performed on industrial and commercial power systems without requiring cross-references to other texts.

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The Gold Book Working Group acknowledges and wholeheartedly thanks Helen L. Garfinkle for her meticulous editorial work on this recommended practice. Her patience and exceptional organizational skills pushed this project along quickly and without incident. Both the IEEE Standards Association and the Gold Book Working Group are grateful for her expertise.

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IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems

Chapter 1 Introduction

1.1 Objectives and scope

The objective of this book is to present the fundamentals of reliability analysis applied to the planning and design of industrial and commercial electric power distribution systems. The intended audience for this material is primarily consulting engineers and plant electrical engineers [and technicians](#).

The design of reliable industrial and commercial power distribution systems is important because of the high cost associated with power outages. It is necessary to consider the cost of power outages when making design decisions for new power distribution systems as well as to have the ability to make quantitative “cost-versus-reliability” trade-off studies. The lack of credible data concerning equipment reliability and the cost of power outages has hindered engineers in making such studies. [This revision of IEEE Std 493™ overcomes these obstacles.](#)

The authors of this book have attempted to provide sufficient information so that reliability analyses can be performed on [industrial and commercial](#) power systems without requiring cross-references to other texts. Included are the following:

- Basic concepts of reliability analysis by probability methods
- Fundamentals of power system reliability evaluation
- Economic evaluation of reliability
- [Recent](#) cost of power outage data
- [New extensive mechanical and electrical](#) equipment reliability data—[Complete U.S. Army Corp of Engineers Power Reliability Enhancement Program \(PREP\) database](#)
- Examples of reliability analysis [of various industrial distribution system operating configurations](#)

~~In addition, discussion and information are provided on~~

- [7 × 24 continuous power](#)
- [Voltage sag analysis](#)
- Emergency and standby power
- ~~Electrical preventive maintenance~~
- Evaluating and improving the reliability of existing ~~facilities~~[electrical system](#)
- Preventative maintenance
- [Reliability and maintainability verification](#)
- [Standard data collection techniques](#)

[The following chapters present a detailed discussion of factors that impact the planning and design of industrial and commercial power systems](#)

~~Two new chapters have been added to this edition of IEEE Std 493:~~

[Chapter 2: Basic concepts of reliability](#)

[Chapter 3: Planning and design](#)

[Chapter 4: Evaluating and improving the reliability of an existing electrical system](#)

[Chapter 5: Preventative maintenance Chapter 6: Emergency and standby power Chapter 7: Voltage sag analysis](#)

[Chapter 8: 7 × 24 continuous power facilities](#)

[Chapter 9: Reliability and maintainability verification](#)

~~Chapter 9, Voltage sag analysis~~

[Chapter 10: Summary of equipment reliability data](#)

~~Chapter 10, Reliability compliance testing for emergency and standby power systems~~

[Chapter 11: Data collection](#)

[The appendixes \(renamed *annexes*\) of IEEE Std 493-1997¹ are included in this revision of the *IEEE Gold Book*[™]. One new annex, Annex Q, has been added to provide additional informative material on the reliability analysis of industrial and commercial power systems.](#)

[Several new reliability concepts \[i.e., inherent availability \(Ai\) and operational availability \(Ao\)\] are introduced in this version of the *IEEE Gold Book*. The inherent frequency and duration of load point interruptions is used to compare designs based on the mean time to repair \(MTTR\) a component. The MTTR a component is defined as only the average time to repair that component but does not include the logistics time \(e.g., to identify and isolate the component on forced outage\). The operational frequency and duration of load point interruptions includes the mean downtime \(MDT\) \(i.e., the mean duration of the component maintenance and forced outage events\). Other reliability studies define the operational frequency and duration of load point interruptions where the MDT excludes the maintenance downtimes \(Mdts\). These concepts are presented in detail in Chapter 2.](#)

~~Chapter 9 meets the demand for a methodology for estimating the frequency of voltage sags (which may interrupt processes and systems) at industrial and commercial sites. Chapter 10 presents a methodology for estimating the number of tests required to demonstrate reliability compliance of devices and systems while considering the reliability constraints dictated by the manufacturer and the customer.~~

~~New appendixes have been added to IEEE Std 493, and existing appendixes have been updated as follows:~~

~~Appendix J, “Summary of CIGRE 13.06 Working Group Worldwide Reliability Data and Maintenance Cost Data on High Voltage Circuit Breakers Above 63 kV,” contains a summary of the most significant reliability data and maintenance cost data from two CIGRE 13.06 Working Group worldwide reliability surveys of high voltage circuit breakers rated 63 kV and above~~

~~Appendix M, “Reliability/Availability Guarantees of Gas Turbines and Combined Cycle Generating Units,” contains one manufacturer’s suggestion on how to write a reliability/availability guarantee when industrial firms are purchasing gas turbine generating units or combined cycle units.~~

~~Appendix N, “Transmission Line and Equipment Outage Data,” contains the failure rates of transmission line equipment that can be used for predicting voltage sags at a particular industrial or commercial site caused by transmission line outages on adjacent feeders and/or from the entire electric network configuration.~~

~~Appendix O, “Interruption Costs, Consumer Satisfaction and Expectations for Service Reliability,” presents a recent study on the cost of service interruptions to various industrial and commercial types. This data can be used for evaluating the cost reliability worth of various industrial and commercial electrical configurations.~~

~~Appendix P, “Survey Results of Low Voltage Circuit Breakers as Found During Maintenance Testing,” contains the results of a low voltage circuit reliability survey achieved through the use of available results from testing during preventive maintenance.~~

1.2 Summary of contents of each chapter

Chapter 2 provides the theoretical background for the reliability analysis used in other chapters. Some basic concepts of probability theory are discussed as these are essential to

¹Information on references can be found in 1.4.

the understanding and development of quantitative reliability analysis methods. Definitions of terms commonly used in system reliability analysis are also included.

Chapter 3 provides a description of how to make quantitative reliability and availability predictions for proposed new and existing configurations of industrial power distribution systems. A discussion is presented on the important factors that must be considered in the reliability analysis of industrial and commercial power systems. The *Gold Book Standard Network* configuration and the results of various reliability methodologies are presented to enable validation of existing and future reliability computerized methodologies. Seven numerical examples are presented and a reliability-cost/reliability-worth methodology presented. The latest survey data on the cost of interruptions to various facilities is presented. A quantitative reliability analysis includes making a disciplined evaluation of alternate power distribution system design choices. When costs of power outages at the various building and plant locations are factored into the evaluation, the decisions can be based upon *total owning cost* over the useful life of the equipment rather than simply the *first cost* of the system. The material in this book should enable engineers to make more use of quantitative cost vs. reliability trade-off studies during the design of industrial and commercial power systems.

The objective of Chapter 4 is to provide the facility engineer with critical issues that should be analyzed from various perspectives considering their system electrically and physically and inquiring about the utility’s system. The chapter provides a list of issues that the engineer should address:

- a) See that faults are properly isolated and that critical loads are not vulnerable to interruption or delayed repair.
- b) Analyze the critical areas and evaluate the need for special restoration equipment, spare parts, or procedures.

- c) Based on probability and economic analysis, make capital or preventive maintenance investments as indicated by the analysis.
- d) Make carefully documented contingency (catastrophe) plans.
- e) Check the quality of the power supply from the utility and throughout the plant to determine if the equipment is vulnerable to premature failure.
- f) Develop preventive maintenance, checking, and logging procedures to ensure continuous optimum reliability performance of the plant.

The objective of Chapter 5 is to illustrate the important role preventative maintenance plays in the availability of systems in industrial plants and commercial buildings. Details of “when,” “how,” and “how often” can be obtained from other sources that are defined in the chapter. Of the many factors involved in availability, preventive maintenance often receives meager emphasis in the design phase and operation of distribution systems when it can be a key factor in high availability. Large expenditures for systems are made to provide the desired reliability; however, failure to provide timely, high-quality preventive maintenance leads to system or component malfunction or failure and prevents obtaining the intended design goal.

Chapter 6 presents an overview of common types of emergency and standby power systems used by most industries to achieve increased reliability in power supply to loads. No attempt is made to list and describe every type of existing system that may be classified as an emergency or standby power system. For example, fuel cells continue to be developed and researched for a wide range of applications. At this time, however, most would agree their cost prohibits attractive practical use in general industrial and commercial applications for emergency and standby power.

Chapter 7 presents a method for voltage sag coordination that is an important improvement in the power quality field. The procedure enables customers, utilities, and equipment manufacturers to quantify the performance of their process, supply, or device. This will no doubt lead to a better understanding of spurious trips and an improvement in performance.

Chapter 8 presents a *reliability block diagram* (RBD) methodology to conduct a probability/reliability study of a 7×24 continuous power facility. Momentary interruptions of the electrical power can have huge financial consequences. The chapter provides a methodology of defining *failure* in a 7×24 facility. Specialty equipment, such as uninterruptible power supplies (UPS), emergency generators, and automatic static transfer switches (ASTS) are used to supplement utility power and are discussed in detail in this chapter.

Chapter 9 presents a generalized sequential test plan for demonstrating whether a power system and/or its parts comply with the specifications dictated by the customer and manufacturer. The number of observed system failures vs. the number of tests required for compliance evaluation is shown graphically. The methodology provides a means of estimating the number of tests required to demonstrate reliability compliance of devices and systems.

Chapter 10 summarizes the reliability data collected from equipment reliability surveys and a data collection program over a period of 35 years or more. This data is the most comprehensive database publicly available on electrical and mechanical equipment reliability in the world. The reliability survey data contained in this book provide historical experience to those who have not been able to collect their own data. Such data can be an aid in analyzing, designing, or redesigning an industrial or commercial system and can provide a basis for the quantitative comparison of alternate designs.

Chapter 11 presents the standard data collection techniques that include the essential categories of information and data essential for reliability modeling including maintenance activities. Categories such as site identification, site one-line drawings, nameplate information, critical equipment designation and sparing, and maintenance data are discussed, and the necessary data collection forms presented. The

[information contained in the data collected provides the analyst with all the necessary data to populate a reliability model.](#)

1.2 IEEE reliability surveys of industrial plants

From 1973 through 1996, the Power Systems Reliability Subcommittee of the Power Systems Engineering Committee of the IEEE Industry Applications Society conducted and published the results of extensive surveys of the reliability of electrical equipment in industrial plants and also the cost of power outages for both industrial plants and commercial buildings. This included motors, motor starters, generators, power transformers, rectifier transformers, circuit breakers, disconnect switches, bus duct, switchgear bus bare, switchgear bus insulated, open wire, cable, cable joints, cable terminations, and electric utility power supplies. The results from these surveys have been published in 16 IEEE committee reports, 15 of which are included in this book in Appendixes A, B, C, D, E, G, H, K, and P. Appendix F gives the procedure used for conducting these surveys. It has been considered important that the “reasons for conducting the survey” be written down at the beginning of each new survey. It has also been considered important that the final report receive both oral and written discussion at the end of each survey. Some of the IEEE surveys have also included the cost of power interruptions, critical service loss duration time, and plant restart time. The most important results from these 16 surveys have been summarized in Chapters 2, 3, and 5. Table 3-2 contains a summary of the latest equipment reliability data from these surveys, and these values are suggested for use in the absence of better data that may be available from the reader’s own experience. Table 3-1 presents a guide of where to look in this book for additional reliability data for each of several equipment categories.

Four important equipment reliability surveys conducted by others have been summarized and included as Appendixes I, J, and N; these appendixes supplement the IEEE equipment reliability surveys in some categories in which there has been little or no data and in other categories in which the data is more recent and/or much more extensive. These four equipment reliability surveys include

- Cable, cable splices, and cable terminations
- High voltage circuit breakers above 63 kV
- Diesel and gas turbine generating units
- Transmission lines and terminal equipment

A paper on electrical service interruption costs is presented in Appendix O.

The reliability survey data contained in this book

1.3 How to use this book

[The authors of this book have made it a self-contained body of knowledge in which reliability analyses can be performed on industrial and commercial power systems without requiring cross-references to other texts. Each chapter addresses the critical issues affecting the reliability of industrial and commercial power distribution systems. For example, those wishing to obtain the latest equipment reliability and maintainability data should go directly to Chapter 10 and wishing to obtain the most recent data on the cost of electrical interruptions to industrial plants or commercial buildings should consult Chapter 3. Chapter 11 provides the standard data collection techniques to capture the reliability data at any industrial and/or commercial facility. The summary of chapter content in 1.2 provides a guide for users to address their specific concerns in the reliability analysis of their industrial and commercial power systems.](#)

1.4 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 493-1997, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (*IEEE Gold Book*).²

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

~~The methods of reliability analysis provided in this book are based upon probability and statistics. Some users of this book may wish to read Chapter 8 on basic probability concepts before reading Chapter 2 on planning and design. Other users may wish to start with Chapter 2 and not wish to attempt to fully understand the derivation of the statistical formulas given in 2.1.9 and 2.1.11.1.~~

~~The most important parts of planning and design are covered in 2.1 and 2.2 on fundamentals of power system reliability evaluation and on the economic evaluation of reliability. Chapter 7 gives seven examples using these methods of analysis. These examples cover some of the most common decisions that engineers are faced with when designing a power distribution system. Some discussion on the limitations of reliability and availability predictions is included in the latter part of 7.1.~~

~~Those wishing to obtain equipment reliability data should go to Chapter 3. Those wishing to obtain data on the cost of electrical interruptions to industrial plants or commercial buildings should consult 2.2. Any data on costs may need to be updated to take into account the effects of inflation.~~

~~The importance of electrical preventive maintenance in planning and design is covered in 2.3 and 2.4. Chapter 5 discusses the subject in further detail and contains data showing the effect of maintenance quality on equipment failure rates.~~

~~Many reliability studies need to be followed up by considerations for emergency and standby power. This subject is covered in Chapter 6 and may also be considered part of planning and design.~~

~~An approach to evaluating and upgrading the reliability of an existing plant is presented in Chapter 4. Some users of this book may wish to start with this chapter.~~

Chapter 2

Basic concepts of reliability

2.1 Introduction

This chapter provides the theoretical background for the reliability analysis used in other chapters. Some basic concepts of probability theory are discussed, as these are essential to the understanding and development of quantitative reliability analysis methods. Definitions of terms commonly used in system reliability analysis are also included.

2.2 Definitions

For the purpose of this document, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B3]¹ should be referenced for terms not defined in this subclause.

~~The following definitions should be used in conjunction with this recommended practice:~~

Some commonly used terms in system reliability analyses are defined here; these terms are also used in the wider context of system reliability activities. These definitions are referenced in several reliability publications and the formulas can be verified in the Reliability Analysis Center's *Reliability Toolkit: Commercial Practices Edition*, page 12 [B7], or MIL-STD-339 [B5].

2.2.1 availability: The ability of an item—under combined aspects of its reliability, maintainability, and maintenance support—to perform its required function at a stated instant of time or over a stated period of time.

~~As applied either to the performance of individual components or to that of a system, it is the long term average fraction of time that a component or system is in service and satisfactorily performing its intended function. An alternative and equivalent definition for availability is the steady state probability that a component or system is in service.~~

2.2.2 component: A piece of electrical or mechanical equipment ~~a line or circuit, or a section of a line or circuit, or a group of items that is~~ viewed as an entity for the purpose of reliability evaluation.

~~**1.4.3 electrical equipment:** A general term including materials, fittings, devices, appliances, fixtures, apparatus, machines, etc., used as a part of, or in connection with, an electric installation.~~

~~**1.4.4 electrical preventive maintenance:** A system of planned inspection, testing, cleaning, drying, monitoring, adjusting, corrective modification, and minor repair of electrical equipment to minimize or forestall future equipment operating problems or failures, which, depending upon equipment type, may require exercising or proof testing.~~

~~**1.4.5 expected failure duration:** The expected or long term average duration of a single failure event.~~

~~**1.4.6 expected interruption duration:** The expected, or average, duration of a single load interruption event.~~

~~**1.4.7 exposure time:** The time during which a component is performing its intended function and is subject to failure.~~

2.2.3 failure (f): The termination of the ability of a component or system to perform a required function.

2.2.4 failure rate (L): The mean (arithmetic average) is the number of failures of a component and/or system per unit exposure time. The most common unit in reliability analyses is hours (h) or years (y).

Therefore, the failure rate is expressed in failures per hour (f/h) or failures per year (f/y). *Syn: forced outage rate.*

1.4.8 failure: Any trouble with a power system component that causes any of the following to occur:

- Partial or complete plant shutdown, or below standard plant operation
- Unacceptable performance of user's equipment
- Operation of the electrical protective relaying or emergency operation of the plant electrical system
- De energization of any electric circuit or equipment

A failure on a public utility supply system may cause the user to have either of the following:

- A power interruption or loss of service
- A deviation from normal voltage or frequency outside the normal utility profile

A failure on an in-plant component causes a forced outage of the component; that is, the component is unable to perform its intended function until it is repaired or replaced. The terms "failure" and "forced outage" are often used synonymously.

1.4.10 forced outage: An outage (failure) that cannot be deferred.

1.4.11 forced unavailability: The long term average fraction of time that a component or system is out of service due to a forced outage (failure).

2.2.5 inherent availability (A_i): The instantaneous probability that a component or system will be up or down. A_i considers only downtime for repair to failures. No logistics time, preventative maintenance, etc., is included.

2.2.6 maintenance downtime (Mdt): The total downtime for scheduled maintenance (including logistics time, spare parts availability, crew availability, etc.) for a given time period (T_p) (hours).

¹The numbers in brackets correspond to those of the bibliography in 2.11.

2.2.7 mean downtime (MDT): The average downtime caused by scheduled and unscheduled maintenance, including any logistics time. *Syn: mean time to restore system (MTTRS).*

2.2.8 mean time between failures (MTBF): The mean exposure time between consecutive failures of a component.

2.2.9 mean time between maintenance (MTBM): The average time between all maintenance events, scheduled and unscheduled, and also includes any associated logistics time.

~~The mean exposure time between consecutive failures of a component. It can be estimated by dividing the exposure time by the number of failures in that period, provided that a sufficient number of failures has occurred in that period.~~

2.2.10 mean time to failure (MTTF): The mean exposure time between consecutive repairs (or installations) of a component and the next failure of that component. MTTF is commonly found for non-repairable items such as fuses or bulbs.

2.2.11 mean time to maintain (MTTM): The average time it takes to maintain a component, including logistics time. MTTM is primarily a measure of the preventative maintenance frequency and durations.

2.2.12 mean time to repair (MTTR or simply r): The mean time to replace or repair a failed component.

Logistics time associated with the repair, such as parts acquisitions, crew mobilization, are not included. It can be estimated by dividing the summation of repair times by the number of repairs and, therefore, is practically the average repair time. The most common unit in reliability analyses is hours (h/f).

~~4.12 interruption: The loss of electric power supply to one or more loads.~~

~~1.4.13 interruption frequency: The expected (average) number of power interruptions to a load per unit time, usually expressed as interruptions per year.~~

~~1.4.16 minimum cut set: A set of components that, if removed from the system, results in loss of continuity to the load point being investigated and that does not contain as a subset any set of components that is itself a cut set of the system.~~

2.2.13 operational availability (Ao): The instantaneous probability that a component or system will be up or down, but differs from A_i in that it includes *all* downtime. Included is downtime for unscheduled (repair due to failures) and scheduled maintenance, including any logistics time.

~~1.4.17 offline system: A system that is dormant until it is called upon to operate, such as a diesel generator that is started up when a power failure occurs.~~

~~1.4.18 online system: A system that is operating at all times, such as an inverter supplied by dc power via the primary power source through a battery charger.~~

~~1.4.19 outage: The state of a component or system when it is not available to properly perform its intended function due to some event directly associated with that component or system.~~

2.2.14 reliability: The ability of a component or system to perform required functions under stated conditions for a stated period of time.

NOTE—The term *reliability* is also used as a reliability characteristic (metric) denoting a probability of success or a success ratio. In general usage, reliability refers to system performance over time.²

~~**1.4.20 repair time:** The repair time of a failed component or the duration of a failure is the clock time from the occurrence of the failure of a component to the time when the component is restored to service, either by repair of the failed component or by substitution of a spare component for the failed component. (Also called the duration of a failure). It includes time for diagnosing the trouble, locating the failed component, waiting for parts, repairing or replacing, testing, and restoring the component to service. It is not the time required to restore service to a load by putting alternate circuits into operation. The terms “repair time” and “forced outage duration” are often used synonymously.~~

2.2.15 repair downtime (Rdt): The total downtime for unscheduled maintenance (excluding logistics time) for a given T_p (hours).

2.2.16 repair logistics time (Rlt): The total logistics time for unscheduled maintenance for a given T_p (hours).

2.2.17 system: A group of components connected or associated in a fixed configuration to perform a specified function.

²Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

~~1.4.21 scheduled outage: An outage that results when a component is deliberately taken out of service at a selected time, usually for purposes of construction, maintenance, or repair.~~

~~1.4.22 scheduled outage duration: The period from the initiation of a scheduled outage until construction, preventive maintenance, or repair work is completed and the affected component is made available to perform its~~

intended function.

~~1.4.23 scheduled outage rate: The mean number of scheduled outages of a component per unit exposure time.~~

~~1.4.24 switching time: The period from the time a switching operation is required due to a component failure until that switching operation is completed. Switching operations include such operations as throwover to an alternate circuit, opening or closing a sectionalizing switch or circuit breaker, reclosing a circuit breaker following a trip out due to a temporary fault, etc.~~

2.2.18 total downtime events (Tde): The total number of downtime events (including scheduled maintenance and failures) during the T_p (previously referred to as *all actions, maintenance, and repair*).

2.2.19 total failures (Tf): The total number failures during the T_p .

2.2.20 total maintenance actions (Tma): The total number of scheduled maintenance actions during the T_p .

2.2.21 total period (Tp): The calendar time over which data for the item was collected (hours).

2.2.22 year (y): The unit of time measurement approximately equal to 8765.81277 hours (h). Any rounding of this value will have adverse effects on analyses depending on the magnitude of that rounding: 8766 is used commonly as it is the result of rounding to 365.25×24 (which accounts for a leap year every 4th year); 8760, which is 365×24 , is the most commonly used value in power reliability field. By convention, 8760 will be used throughout this recommended practice.

~~1.4.26 unavailability: The long-term average fraction of time that a component or system is out of service due to failures or scheduled outages. An alternative definition is the steady-state probability that a component or system is out of service due to failures or scheduled outages. Mathematically, $\text{unavailability} = (1 - \text{availability})$.~~

2.3 Calculation reference

A summary of the definitions is compiled in Table 2-1. This table is supplied for your quick reference for some of the formulas that are provided with definition later in the chapter. These calculations are also useful in the Chapter 10.

Table 2-1—Definition summary

<u>Calculated data</u>	<u>Formula for calculation</u>
<u>A_i, inherent availability</u>	<u>$A_i = \text{MTBF} / (\text{MTBF} + \text{MTTR})$</u>
<u>A_o, operational availability</u>	<u>$A_o = \text{MTBM} / (\text{MTBM} + \text{MDT})$</u>
<u>λ, failure rate (f/h)</u>	<u>$\lambda = T_f / T_p$</u>
<u>λ, failure rate (f/y)</u>	<u>$\lambda = T_f / (T_p / 8760)$</u>
<u>MDT, mean downtime (h)</u>	<u>$\text{MDT} = (\text{Rdt} + \text{Rlt} + \text{Mdt}) / \text{Tde}$</u>
<u>MTBF, mean time between failures (h)</u>	<u>$\text{MTBF} = T_p / T_f$</u>
<u>MTBM, mean time between maintenance (h)</u>	<u>$\text{MTBM} = T_p / \text{Tde}$</u>
<u>MTTM, mean time to maintain (h)</u>	<u>$\text{MTTM} = \text{Mdt} / \text{Tma}$</u>
<u>MTTR, mean time to repair (h)</u>	<u>$\text{MTTR} = r = \text{Rdt} / T_f$</u>
<u>R(t), reliability</u>	<u>$R(t) = e^{-\lambda t}$</u>

Table 2-1—Definition summary (continued)

<u>Calculated data</u>	<u>Formula for calculation</u>
<u>Downtime hours per year (DHY)</u>	<u>$\text{DHY} = (1 - A_o) \times 8760$</u>
<u>λ_r, downtime hours per year (DHY)</u>	<u>$\text{DHY} = \lambda_r$, where λ is the failure rate per year</u>

2.4 Acronyms and abbreviations

A_i inherent availability

A_o operational availability

ASTS automatic static transfer switch

CDF cumulative distribution function

FMEA failure mode and effects analysis

Mdt maintenance downtime

MDT mean downtime

m-g motor-generator

MTBF mean time between failures

MTBM ean time between maintenance

MTTF mean time to failure

MTTR mean time to repair

O&M operations and maintenance

PDF probability density function

PDU power distribution unit

RBD reliability block diagram

RCM reliability centered maintenance

Rdt repair downtime

Rlt repair logistics time

SPOF single point of failure

Tde total downtime events

Tf total failures

Tma total maintenance actions

Tp total period

2.5 Review of basic probability

2.5.1 Sample space

Sample space is the set of all possible outcomes of a phenomenon. For example, consider a system of three components. Assuming that each component exists either in the operating or “up” state or in the failed or “down” state, consider the sample space:

$S = (1U, 2U, 3U), (1D, 2U, 3U), (1U, 2D, 3U), (1U, 2U, 3D), (1D, 2D, 3U), (1D, 2U, 3D), (1U, 2D, 3D), (1D, 2D, 3D)$

Where iU and iD denote that the component i is up or down, respectively. The possible outcomes of a system are also called *system states*, and the set of all possible system states is called *system state space*.

2.5.2 Event

In the example of the three-component system, the descriptions $(1D, 2D, 3U)$, $(1D, 2U, 3D)$, $(1U, 2D, 3D)$, and $(1D, 2D, 3D)$ define the events in which two or three components are in the failed state. Assuming that a minimum of two components is needed for successful system operation, this set of states (A) also defines the system failure. A is, therefore, a set of system states, and the event $A(N)$ is said to have occurred if the system is in a state that is a

member of set A.

2.5.3 Combinatorial properties of event probabilities

Follows are certain combinatorial properties of event probabilities that are useful in reliability analysis.

2.5.3.1 Addition rule of probabilities

Two events, A1 and A2, are mutually exclusive if they cannot occur together. For events A1 and A2 that are not mutually exclusive (that is, events which can happen together), see Equation (2.1).

$$\underline{P(A1 * A2) = P(A1) + P(A2) - P(A1 \cap A2)} \quad (2.1)$$

where

$$\underline{P(A1 \cup A2)}$$

$$\underline{P(A1 \cap A2)}$$

is the probability of A1 or A2, or both happening

is the probability of A1 and A2 happening together

When A1 and A2 are mutually exclusive, they cannot happen together; that is, $P(A1 \cap A2) = 0$, therefore Equation (2.1) reduces to Equation (2.2):

$$\underline{P(A1 * A2) = P(A1) + P(A2)} \quad (2.2)$$

Where A1 and A2 are mutually exclusive.

2.5.3.2 Multiplication rule of probabilities

If the probability of occurrence of event A1 is affected by the occurrence of A2, then A1 and A2 are not independent events.

The conditional probability of event A1, given that event A2 has already occurred, is denoted by $P(A1 | A2)$ and Equation (2.3):

$$\underline{P(A1 | A2) = P(A1 \cap A2) / P(A2)} \quad (2.3)$$

Equation (2.4) is also used to calculate the conditional probability:

$$\underline{P(A1 \cap A2) = P(A1 | A2) P(A2)} \quad (2.4)$$

When, however, events A1 and A2 are independent, that is, the occurrence of A2 does not affect the occurrence of A1, use Equation (2.5):

$$\underline{P(A1 \cap A2) = P(A1) P(A2)} \quad (2.5)$$

2.5.3.3 Complementation

A2¹ is used to denote the complement of event A1. The complement A2¹ is the set of states that are not members of A1. For example, if A1 denotes states indicating system failure, then the states not representing system failure make A2¹ [see Equation (2.6)].

$$P(A21) = 1 - P(A1) \quad (2.6)$$

2.6 Reliability and availability

In the reliability engineering discipline, the terms *reliability* and *availability* have specialized technical meanings. In general, reliability refers to system performance over time. And unfortunately, reliability is often shorthand for *reliability engineering* and its practice, results, etc. Reliability engineering is a design engineering discipline that applies scientific knowledge to assure a product will perform its intended function for the required

duration within a given environment. This includes designing in the ability to maintain, test, and support the product throughout its total life cycle. This is accomplished concurrently with other design disciplines by contributing to the selection of the system architecture, materials, processes, and components—both software and hardware— followed by verifying the selections made by thorough analysis and test. Availability generally refers to the quality or state of being immediately ready for use.

2.6.1 General concepts

The term *reliability* refers to the notion that the system performs its specified task correctly for a certain time duration. The term *availability* refers to the *readiness* of a system to immediately perform its task—at a particular time. Both terms have precise definitions within reliability engineering discipline and typically have specified equations or methods to provide quantitative metrics for each of them. A rocket must be very reliable for the duration of the short mission, but might not be very available as it may sit in a repair state for extended periods of time.

On the other hand, power for communications facilities needs to be highly available, implying little downtime. Where the components of the system might be unreliable, the redundancies of that system can help achieve high availability.

2.6.2 Definitions

2.6.2.1 Reliability

If the time, t , over which a system must operate and the underlying distributions of failures for its constituent elements are known, then the system reliability can be calculated by taking the integral, essentially the area under the curve defined by the probability density function (PDF, see 2.9), from t to infinity, as shown in Equation (2.7).

$$R(t) = \int_t^{\infty} f(t)dt \quad (2.7)$$

where

$R(t)$ is the reliability of a system from time t to infinity
 $f(t)$ is the PDF

2.6.2.2 Availability

2.6.2.2.1 Availability assumptions

Generally in this document, availability will be used as a mathematical term being either the percent of time a system is immediately ready for use, or as an instantaneous probability of the system being immediately ready for use.

Generally, availability metrics fall into two distinct subsets: *inherent availability* (A_i) and *operational availability*

(Ao). Ai considers component failure rates and the average repair time for those components. Ao goes beyond Ai in that maintenance downtimes (Mdt), parts procurement times, logistics, etc., are included. Although Ao provides a “truer” availability of a system, Ai provides a metric that is not tainted by local facility characteristics, such as spare part supplies, planned outages, etc. Ai is useful as a common metric for comparing multiple facilities and measuring particular facilities against a predetermined availability goal.

Availability analyses need to have an explicit listing of the assumptions used for each unique analysis. For example, if a facility will go down for maintenance, but the outage is not deemed critical, then that outage might not be included in that analysis. On the other hand, if a mission critical facility has a planned maintenance event on a redundant piece of equipment, then that planned outage could be included to capture the additional exposure to risk as the redundancy of the system is temporarily lost.

2.6.2.2.2 Inherent availability definition

In general, availability is immediate readiness for use. For this recommended practice, we only consider Ai and calculate the metric for Ai explicitly as shown in Equation (2.8):

$$A_i = \frac{MTBF}{MTBF + MTTR} \quad (2.8)$$

where

MTBF is mean time between failures

MTTR is mean time to repair

If the system never failed, the MTBF would be infinite and Ai would be 100%. Or, if it took no time at all to repair the system, MTTR would be zero and again the availability would be 100%. Figure 2-1 is a graph showing availability as a function of MTBF and MTTR [availability is calculated using Equation (2.8)]. Note that you can achieve the same availability with different values of MTBF and MTTR. With lower MTBF, lower levels of MTTR are needed to achieve the same availability and vice versa.

2.6.2.2.3 Inherent availability misinterpretations/limitations

Power availability metrics tend to be reported as a function of “9’s.” This refers to the quantity of 9’s past the decimal point. A facility with an availability of 0.99999 would be referred to as having 5-9’s.

A common misunderstanding—and misuse—of the metric is the interpretation that a mean downtime (MDT) can be extracted from an availability metric. For example, a common proclamation is that a facility that has achieved 5-9’s availability can expect an average downtime of approximately 5 min per year. It is mathematically true that the system will be down an average of 5 min per year over the long run, i.e., as $t \rightarrow \infty$. However, if MTBF is known, or calculated a priori, to be 87 660 h (10 y), then the expected duration of the outage will be 52 min.

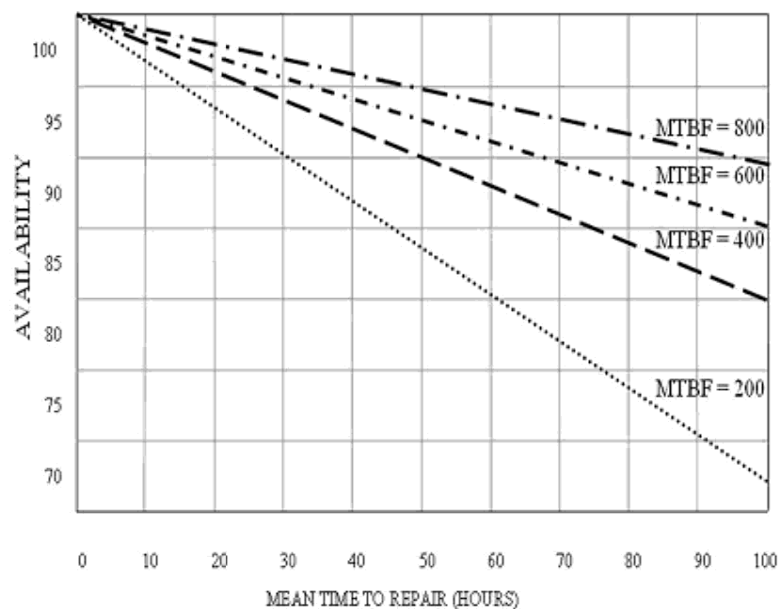


Figure 2-1—Different combinations of MTBF and MTTR yield the same availability

Essentially, an availability metric is a ratio of two parameters. As made clear in 2.6.2.2.2, given an availability metric, there are infinite MTBF and MTTR metrics that can yield the same availability metric. Thus, if availability of a system is estimated through modeling, great care must be taken in extracting system MTBF and MTTR metrics.

2.7 Defining frequency and duration of outages and interruptions, λ , MTBF

The definitions and assumptions associated with frequency and duration data are critical to effectively measuring the reliability of a power system. The choice of metric used to define outages and repair times is dependent on the data used to generate the statistic, which leads to the proper distribution function (see 2.8).

2.7.1 Frequency of failures, outages

Historically, frequency was synonymous with the failure rate (or MTBF), which implied the exponential distribution attribute of having a constant failure rate with randomly occurring events throughout the life of the component or system. The failure distribution of few components is random—to be described by the exponential distribution. Its popularity is a function of the fact that it is the best distribution given the data that is available for most power components.

As data collection efforts continue, time to failure data, coupled with the maintenance practices on that equipment, will produce data that can be tested for best fit for a multiple of distributions, primarily the Weibull (see 2.8.5).

2.7.2 Duration of outages and interruptions

Similarly, the duration of outages has historically been described as the MTTR—implying the exponential distribution. This, again, was due to a lack of detailed data. In considering descriptive statistics to represent the duration of outages, the assumptions, such as the inclusion of scheduled repairs, logistics, spare parts availability, must be explicitly stated.

2.8 Probability distributions

Probability distributions are mathematical equations that describe the probability of a particular event occurring with respect to time. For reliability analysis, what is of great interest is the probability distribution of failure. These functions capture failure characteristics such as wearout failure modes, infant mortality, random, etc. The most common distribution for power reliability analyses (the term *reliability* used in the general sense, as described in 2.6.1) is the exponential distribution. This function describes a random failure mode, where the MTBF is the critical parameter. Others are the Weibull, the Lognormal, etc.

2.8.1 Probability density functions

Each probability distribution has unique PDFs with the notation $f(t)$. The area under that curve shows the relative probability of a failure occurring before time t (see Figure 2-2). That probability, which becomes the cumulative distribution function (CDF), can be calculated by the integral shown in Equation (2.9):

$$F(t) = \int_0^t f(t) dt \quad (2.9)$$

where

$F(t)$ is the probability of a failure occurring before time t $f(t)$ is the PDF of failure

2.8.2 Cumulative distribution function

Plotting $F(t)$ gives us the CDF, which shows the probability of a failure occurring at time t (see Figure 2-3).

Finally, the reliability function $R(t)$ is the probability if a component not failing by time t . Therefore $R(t) = 1 - F(t)$.

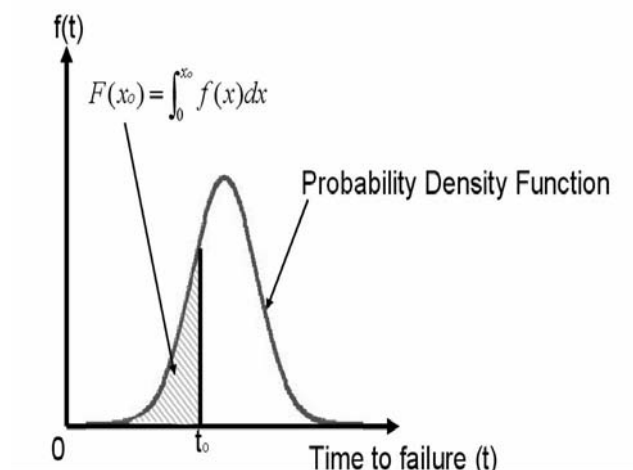


Figure 2-2—Probability of a failure represented by the area under the curve of the PDF

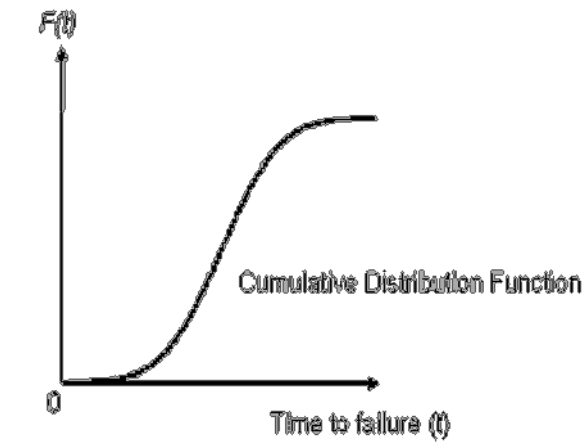


Figure 2-3—The cumulative distribution

2.8.3 Hazard function

The hazard function, or hazard rate, is the instantaneous failure rate for the remaining population at time t . It is denoted as shown in Equation (2.10):

$$H(t) = \frac{f(t)}{R(t)} \quad (2.10)$$

2.8.4 Exponential distribution

The PDF for the exponential distribution is shown in Equation (2.11):

$$f(t) = \lambda e^{-\lambda t} \quad (2.11)$$

Thus, the CDF is shown in Equation (2.12):

$$F(t) = 1 - e^{-\lambda t} \quad (2.12)$$

And the reliability function is shown in Equation (2.13):

$$R(t) = e^{-\lambda t} \quad (2.13)$$

where

- λ is the failure rate (inverse of MTBF)
- t is the length of time the system must function
- e is the base of natural logarithms

It can be seen that the hazard function is as shown in Equation (2.14):

This is to be expected, as the instantaneous failure rate is constant for the exponential distribution.

The most essential characteristic of the exponential distribution, which is the common PDF in availability analyses, is that the failure rate is constant over time—the component is no more likely to fail in its first year of life than it is in its 21st year of life. It should not be assumed that all components exhibit this characteristic. Most do not. Its popularity is a function of the fact that it is the best PDF given the data that supports the reliability metrics of most power components. Essentially, the exponential requires only the MTBF, which can be easily determined by a total component run time and a total of component failure events.

2.8.5 Weibull distribution

The Weibull distribution is one of the most widely used in life data distribution analysis. It is a versatile distribution that can take on the characteristics of other types of distributions, based on the value of the shape parameter beta (β). When $\beta > 1$ then a wearout failure mode is present. When $\beta < 1$ then the part exhibits infant mortality. When $\beta = 1$, then the Weibull distribution is mathematically equal to the *exponential distribution*, implying a random failure mode. The eta (η) parameter is a “location” factor. Where the beta parameter tells us how the part is going to fail, the eta parameter tells us when.

2.8.5.1 PDF and CDF

Equation (2.15) shows the Weibull PDF:

$$f(t, \beta, \eta) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} e^{-\left(\frac{t}{\eta} \right)^{\beta}} \quad (2.15)$$

where

β is the shape parameter
 η is the location parameter

Equation (2.16) shows the Weibull CDF:

$$F(t, \beta, \eta) = 1 - e^{-\left(\frac{t}{\eta} \right)^{\beta}} \quad (2.16)$$

The hazard function for the Weibull distribution is shown in Equation (2.17):

$$H(t, \beta, \eta) = \beta t^{\beta-1} \quad (2.17)$$

When $\beta = 1$, the Weibull distribution is equal to the exponential distribution, as shown in Equation (2.18):

$$F(t, 1, \eta) = 1 - e^{-\left(\frac{t}{\eta} \right)} = 1 - e^{-\left(\frac{t}{\eta} \right)} \quad (2.18)$$

Note the variety in PDF shapes depending on the choice of β , as shown in Figure 2-4.

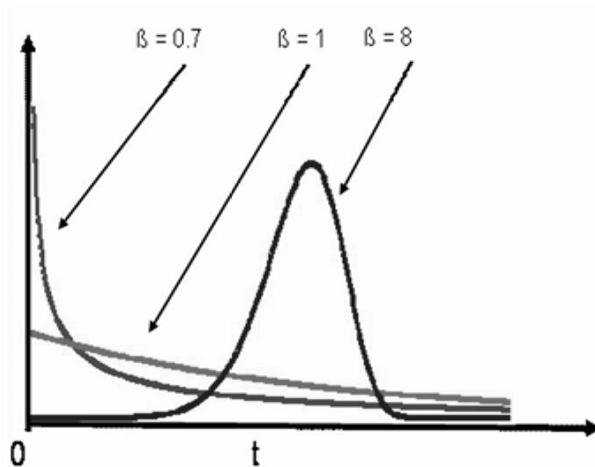


Figure 2-4—Variation of the beta parameter

2.8.6 Calculating reliability for the exponential

If the underlying distribution for each element is exponential and the failure rates, λ_i , for each element are known, then the reliability of the system can be calculated using Equation (2.13).

2.8.6.1 Series reliability

Consider the system represented by the reliability block diagram (RBD) in Figure 2-5.

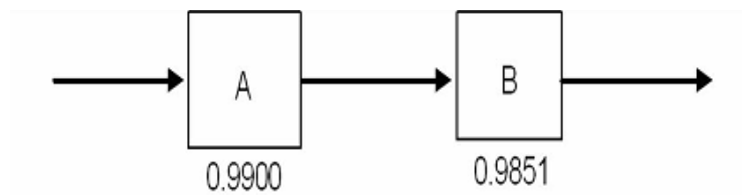


Figure 2-5—Example reliability block diagram

Note—The number above each block in Figure 2-5 is the failure rate λ_i in failures per million hours. The inverse of the failure rate is the MTTF (exponential failure rate assumed). The number below each block is the reliability calculated using Equation (2.13) with $t = 10$ million hours.

2.8.6.1.1 Series configuration—Weakest link

Components A and B in Figure 2-5 are said to be in series, which means all must operate for the system to operate. Since the system can be no more reliable than the least reliable component, this configuration is often referred to as the *weakest link configuration*. An analogy would be a chain; the strength of the chain is determined by its weakest link.

2.8.6.1.2 Series calculation method 1

Since the components are in series, the system reliability can be found by adding together the failure rates of the components. The system failure rate is $0.001000 + 0.001500 = 0.002500$. The reliability is shown in Equation (2.19):

$$R(t) = e^{-0.0025 \times 10} = 0.9753 \quad (2.19)$$

2.8.6.1.3 Series calculation method 2

Alternatively, we could find the system reliability by multiplying the reliabilities of the two components as follows: $0.9900 \times 0.9851 = 0.9753$.

2.8.6.2 Reliability with redundancy

Now consider the RBD shown in Figure 2-6.

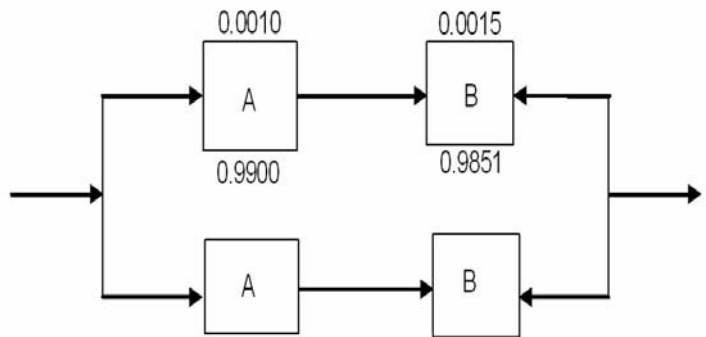


Figure 2-6—RBD of a system with redundant components

NOTE—The number above each block in Figure 2-6 is the failure rate in failures per million hours. The inverse of the failure rate is the MTTF (exponential failure rate assumed). The number below each block is the reliability.

The system represented by the block diagram in Figure 2-6 has the same components (A and B) used in Figure 2-5, but two of each component are used in a configuration referred to as *redundant* or *parallel*. Two paths of operation are possible. The paths are top A-B or bottom A-B. If either of two paths is intact, the system can operate. The reliability of the system is most easily calculated by finding the probability of failure ($1 - R(t)$) for each path, multiplying the probabilities of failure (which gives the probability of both paths failing), and then subtracting the result from 1. The reliability of each path was found in the previous example. Next, the probability of a path failing is found by subtracting its reliability from 1. Thus, the probability of either path failing is $1 - 0.9753 = 0.0247$. The probability that both paths will fail is $0.0247 \times 0.0247 = 0.0006$. Finally, the reliability of the system is $1 - 0.0006 = 0.9994$, a significant improvement over the series-configured system, which had a reliability of 0.9753.

2.8.6.3 N + X redundancy

System redundancy is not restricted to simply having twin systems. Where N is defined as the required piece of equipment to achieve an operational system, 2N would, in turn, imply that there is double the capacity, i.e., 1 of 2 are required to operate for system success. In some facilities, where there is a full 2N philosophy for redundancy, the facility will often have one additional piece of equipment on each side so that if one of the N pieces of equipment is down for maintenance, the facility still is 2N redundant. This would be the $2(N + 1)$ configuration.

With respect to availability, the following tables represent the availability of a system that requires 1000 kVA of power, assuming that each has an availability of 0.99.

Case 1: Use 1000 kVA generators □ N = 1

Case 2: Use 500 kVA generators □ N = 2

<u>Number of generators</u>	<u>Redundancy</u>	<u>Requirement</u>	<u>Availability</u>
<u>1</u>	<u>N</u>	<u>1 of 1</u>	<u>0.99</u>
<u>2</u>	<u>N + 1</u>	<u>1 of 2</u>	<u>0.9999</u>
<u>3</u>	<u>N + 2</u>	<u>1 of 3</u>	<u>0.999999</u>

<u>Number of generators</u>	<u>Redundancy</u>	<u>Requirement</u>	<u>Availability</u>
<u>2</u>	<u>N</u>	<u>2 of 2</u>	<u>0.98</u>
<u>3</u>	<u>N + 1</u>	<u>2 of 3</u>	<u>0.9997</u>
<u>4</u>	<u>N + 2</u>	<u>2 of 4</u>	<u>0.999996</u>

Case 3: Use 250 kVA generators □ N = 4

<u>Number of generators</u>	<u>Redundancy</u>	<u>Requirement</u>	<u>Availability</u>
<u>4</u>	<u>N</u>	<u>4 of 4</u>	<u>0.96</u>
<u>5</u>	<u>N + 1</u>	<u>4 of 5</u>	<u>0.9990</u>
<u>6</u>	<u>N + 2</u>	<u>4 of 6</u>	<u>0.99998</u>

2.8.6.4 M of N calculations for reliability

Equation (2.20) can be used for calculating the reliability of an m of n system for any arbitrary m or n :

$$R(t) = \sum_{k=m}^n \frac{n!}{k!(n-k)!} (e^{-\lambda k})^k (1 - e^{-\lambda k})^{(n-k)} \quad (2.20)$$

where

n is the total number of components

m is the required components

2.9 Methods of reliability and availability analysis

The intent of the tools in this subclause—and the entire chapter—is to perform availability analyses for systems. These tools, particularly those resulting from the exponential distribution are directly applicable to one family of analyses: analytical. The PDFs introduced in 2.8 can be used to their greatest potential in numerical analyses using Monte Carlo simulation.

2.9.1 Analytical methodologies

Analytical methods utilize logical algebraic formulas to arrive at a closed-form, exact, solution to a model of a

system. Simple systems, as seen in 2.8.6.1, can be calculated with pencil and paper. That exercise grows linearly as the model grows linearly. Several techniques/algorithms streamline the process of calculating availability for large systems.

2.9.1.1 Cut-set

The cut-set method can be applied to systems with simple as well as complex configurations and is a very suitable technique for the reliability analysis of power distribution systems. A cut-set is a “set of components whose failure alone will cause system failure,” and a minimal cut-set has no proper subset of components whose failure alone will cause system failure. The components of a minimal cut-set are in parallel since all of them must fail in order to cause system failure, and various minimal cut-sets are in series as any one minimal cut-set can cause system failure.

2.9.1.2 Network reduction

The network reduction method is useful for systems consisting of series and parallel subsystems. This method consists of successively reducing the series and parallel structures by equivalent components. Knowledge of the series and parallel reduction formulas is essential for the application of this technique.

2.9.1.3 GO algorithm

The GO algorithm, a success-oriented system analysis technique, was originally developed for defense industry applications in the early 1960s. The capability of the GO methodology was drastically improved under the sponsorship of the Electric Power Research Institute (EPRI) with the development of additional analytical techniques (i.e., system interactions, system dependencies, and man-machine interactions) and improved computer software reliability. The popularity of the GO method can be linked to basic characteristics that fault trees do not possess, including: 1) hardware is modeled in a manner more or less the same way as in the system drawings, 2) model modifications can be easily introduced to reflect configuration changes, and 3) the modeling capability is extremely flexible. GO’s success-oriented technique analyzes system performance through straightforward inductive logic. The GO representation of a system, or GO model, can often be constructed directly from engineering drawings, which makes GO a valuable tool for many applications, since it is relatively easy to build and review models.

A system model is first constructed within the GO methodology using a top-down (forward-looking) approach to identify the functions required for successful operation following normal process flow or operational sequences. Secondly, in the GO methodology each of the systems that provide the functionality is modeled to the required level of detail. The level of detail may be at the system, subsystem, or component level depending upon the type of information required and the plant specific information available. The GO models determine all system-response modes: successes, failures, prematures, etc.

GO models consist of arrangements of GO operator symbols and represent the engineering functions of components, subsystems, and systems. The models are generally constructed from engineering (one-line) drawings by replacing engineering elements (valves, motors, switches, etc.) with one or more GO symbols that are interrelated to represent system functions, logic, and operational sequences. The GO software uses the GO model to quantify system performance. The method evaluates system reliability and availability, identifies fault sets, ranks the relative importance of the constituent elements, and places confidence bounds on the probabilities of occurrence of system events reflecting the effects of data uncertainties.

Some key features of the GO method are as follows:

- a) Models follow the normal process flow
- b) Most model elements have one-to-one correspondence with system elements

- c) Models accommodate component and system interactions and dependencies
- d) Models are compact and easy to validate
- e) Outputs represent all system success and failure states
- f) Models can be easily altered and updated
- g) Fault sets can be generated without altering the basic model
- h) System operational aspects can be incorporated
- i) Numerical errors due to pruning are known and can be controlled

The GO procedure uses a set of 17 standard logical operators to represent the logic operation, interaction, and combination of physical equipment and human actions. For example, a type 1 operator represents the logical operation of equipment that either performs, or fails to perform, its function given a proper input or stimulus. The type 2 operator performs the logical OR gate operation where a successful response is generated if any of several inputs is proper, etc. The random variables of the GO methodology include operator inputs called *stimuli* ($S1, S2, \dots, Sn$) and outputs referred to as *responses* ($R1, R2, \dots, Rn$). An operator, which represents equipment responses or human actions and which may itself have associated performance probabilities, processes the input random variable in a prescribed and well-defined way to generate the output random variables. These random variables are given the electrical term *signals* in the GO models.

2.9.2 Numerical methods

2.9.2.1 State space

The state space methodology is founded on a more general mathematical concept called *Markov chains*. Markov chains are a modeling technique that describes a system by the possible states in which it can possess (i.e., state space). For our purpose, a system essentially resides in two distinct states: up or down. The probability of transitioning from one state to the other in a given time period is the critical reliability metric that we are after. Figure 2-7 shows this simple Markov model.

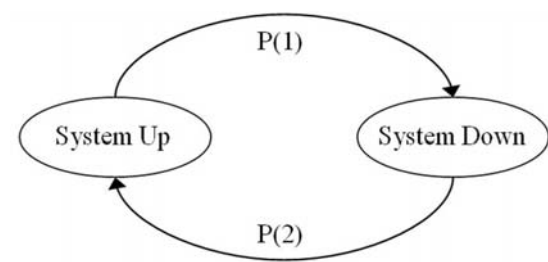


Figure 2-7—Simple Markov model

where

- $P(1)$ is the probability of the system going down in time t
- $P(2)$ probability of the system coming up in time t

However, the true goal of availability analysis is to determine the probability of being in the “up” state—or the time spent in the up state for a given time t . To show this, consider the simpler scenario including only a system with backup generation. Given loss of utility power, the generators will either start automatically, or if that

functionality fails, the generators can be started manually. In those starting phases, the system is “down.” Once started, the system is up. The system will then switch to utility power once available. The system could be down during that switching.

Figure 2-8 shows the associated Markov model for this system. Between each of the possible states are state transitional probabilities that must be known. The solution to the model will be the time spent in the up states vs. the down states.

Solving Markov models is simple only for very simple models, by solving a set of linear equations. The complexity solving these models grows exponentially as the sizes of the models grow linearly. Solutions can be found by using complex numerical analysis methods involving linear algebraic matrix operations, etc. Markov models can also be solved by Monte Carlo techniques described as follows.

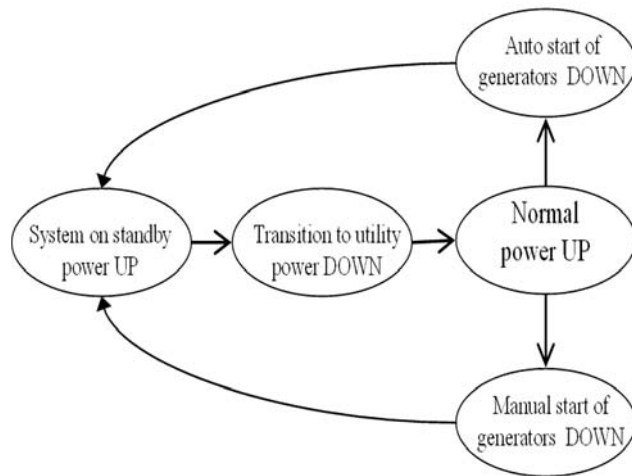


Figure 2-8—Less simple Markov model

2.9.2.2 Monte Carlo simulation

Monte Carlo simulation is the most versatile modeling methodology available. The methodology can be implemented in many forms from simple models in a spreadsheet environment to complex models that are “handcrafted” in a programming language of choice. There are also a variety of simulation software packages that provide drag-and-drop environments that can automate the creation of simulated models for the casual analyst.

2.9.2.3 Simulation basics

The Monte Carlo simulator operates on an iterative process where each “iteration” represents a description of what the system could experience through a set mission life. For instance, if we consider the past experience of a system, including what really failed, that experience was only one of infinite possible outcomes that depended on the failure characteristics of that system.

Thus, Monte Carlo simulation looks forward by considering possible scenarios that could occur in the future—and those scenarios, with their associated likelihoods, is dependent on the failure characteristics applied to the system components. For each iteration, failure times, and the associated repair attributes, are picked for each component in the system. The simulation will then implement the logical relationships of the system to determine the following:

- a) If a failure has occurred in the system prior to the defined mission life.

b) If a failed component(s) takes the system down, what is the duration of downtime.

With these items determined, the availability for the system in that particular iteration can be calculated. Then, as this single iteration is repeated, an average is tabulated of uptime vs. downtime, and duration of downtimes. The average of all the iterations yields expected system availability.

2.10 Performing reliability and availability analyses

The results of availability analyses are extremely sensitive to factors such as underlying assumptions, techniques for calculating availability, and the data used to support the analysis. No results of an analysis should be distributed—let alone trusted—without documentation supporting those attributes. Subtle differences in those attributes can produce drastically different results, results that might be used to drive design decision making. It is the ultimate responsibility of the analyst to be aware of those sensitivities and perform and present analyses with integrity.

2.10.1 Modeling limitations

Cut-set, state space, network reduction, and Boolean algebra are techniques that lend themselves to the casual reliability engineer to analyze small systems, primarily because they can all be accomplished with common desktop PC tools such as spreadsheets, etc. A series of studies recently performed on the *Gold Book Standard Network* have shown that, provided that the assumptions are held equal, each technique produces similar results. The first four techniques however become impractical under certain conditions.

2.10.1.1 Network size

As larger systems are modeled, the sheer size of the analysis becomes burdensome for the analyst. Furthermore, “what-if” sensitivity analyses also become impractical.

2.10.1.2 Smarter distributions

Data collection efforts have expanded the analysts’ tools beyond the classical MTBF analysis. Failure distributions such as the normal, lognormal, Weibull, etc., are being fitted to common failure modes of many critical components in power distribution networks.

2.10.1.3 Modeling hurdles

There are several system attributes that are challenging to model. UPS battery life, for instance, had historically been assumed to be limitless in many analyses, whereas their contribution to power availability is not. Furthermore, Data has shown that standby equipment has differing distributions from their primary counterparts. Thirdly, spare parts availability, human factors, etc., are difficult to capture with the classical approaches to availability analysis.

2.10.2 Modeling solutions

The typical engineer can perform “back of the envelope” analyses easily. Results from these analyses are only as good as the assumed ground rules and the data used. Experience

has shown that analysts who wish to perform availability studies often and consistently should choose a software package to aid in this effort. Packages exist that perform analyses via most of the described methodologies. Once a package is selected, the user should become familiar with the package behavior, the analytical or numerical methodology used, and the underlying limitations of that package.

Chapter 3 uses the minimal cut-set methodology for its examples. Furthermore, the chapter provides a comparison of results from various methodologies.

2.11 Bibliography

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[B3] IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition. New York: Institute of Electrical and Electronics Engineers, Inc.^{3, 4}

[B4] IEEE Std 493TM-1990, *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (IEEE Gold BookTM)*.

[B5] MIL-STD-339 (1998), *Selection and Installation of Wiring and Wiring Devices for Combat and Tactical Vehicles*.⁵

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³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

⁴The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

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Chapter 3 Planning and design

2.1 Fundamentals of power system reliability evaluation

2.1.1 Reliability evaluation fundamentals

3.1 Introduction

2.1.2 Power system design considerations

2.1.3 Definitions

Fundamentals necessary for a quantitative reliability evaluation in electric power systems [involved in planning and designing](#) include definitions of basic terms, discussions of useful measures of system reliability and the basic data needed to compute these indexes, and a description [and references](#) of procedures for system reliability analysis including computation of quantitative reliability indexes.

An important aspect of power system design involves consideration of the service reliability requirements of loads that are to be supplied and the service reliability that will be provided by any proposed system. System reliability assessment and evaluation methods based on probability theory allow the reliability of a proposed system to be assessed quantitatively ~~are finding wide application today~~. Such methods permit consistent, defensible, and unbiased assessments of system reliability that are not otherwise possible.

The quantitative reliability evaluation methods ~~presented here~~ permit reliability indexes for any electric power system to be computed from knowledge of the reliability performance of the constituent components of the system. Thus, alternative system designs can be studied to evaluate the impact on service reliability and cost of changes in component reliability, system configuration, protection and switching scheme, or system operating policy including maintenance practice.

[In this chapter, a description is given of how to make quantitative reliability and availability predictions for proposed new and existing configurations of industrial power distribution systems. A discussion is presented on the important factors that must be considered in the reliability analysis of industrial and commercial power systems. Some of these factors are: reliability indexes, reliability data \(e.g., component failure rates, repair and replacement times, switching times\), definition of interruptions, and reliability equations. Seven examples of industrial system configurations \(e.g., a simple radial system, a primary-selective system, secondary-selective system\) are worked out in detail showing how the failure of individual components affect the overall reliability levels at a point of use within an industrial facility. The following chapters present a detailed discussion of other factors that impact the planning and design of industrial and commercial power systems:](#)

[Chapter 4: Evaluating and improving the reliability of an existing electrical system](#)

[Chapter 5: Preventative maintenance Chapter 6: Emergency and standby power Chapter 7: Voltage sag analysis](#)

[Chapter 8: 7 × 24 continuous power facilities](#)

[Chapter 9: Reliability and maintainability verification Chapter 10: Summary of equipment reliability data](#)

[Chapter 11: Data collection](#)

[Recent surveys on the cost of power interruptions to industrial, commercial, and institutional facilities will be summarized and presented in this chapter. The estimated cost of power interruptions to an individual facility can be factored into the decision as to which type of power distribution system to use. This approach could be used to assist in cost-reliability trade-off decisions in the design of the power distribution system.](#)

~~Terms previously defined in Chapter 1 are commonly used in the survey of the reliability of electric~~

~~equipment in industrial plants (see IEEE Committee Report [B15])¹. Refer to 1.4.~~

3.2 Fundamentals of power system reliability evaluation

3.2.1 System reliability indexes

The basic system reliability indexes (IEEE Std 493TM-1997)¹ that have proven most useful and meaningful in power distribution system design are as follows:

- a) Frequency of load [point](#) interruptions
- b) Expected duration of load point interruption events

These indexes can be readily computed using the methods that will be described ~~later and referenced in this chapter.~~ The two basic indexes (interruption frequency and expected interruption duration) can be used to compute the following indexes that are also useful [in the planning and design of industrial and commercial power systems.](#)

- 1) Total expected (average) interruption time per year (or other time period)
- 2) System availability or unavailability as measured at the load supply point in question
- 3) Expected demand, but unsupplied, energy per year

It should be noted here that the disruptive effect of power interruptions is often non-linearly related to the duration of the interruption. Thus, it is often desirable to compute not only an overall interruption frequency but also frequencies of interruptions categorized by the appropriate durations.

¹~~The numbers in brackets preceded by the letter B correspond to those of the bibliography in 2.5.~~

3.2.2 What is an interruption?

Evaluation of reliability begins with the establishment of an interruption definition. Such a definition specifies the magnitude of the voltage sag and the minimum duration of such a reduced-voltage period that result in a loss of production or other function for the plant, process, or building in question. Frequently, interruption definitions are given only in terms of a minimum duration and assume that the voltage is zero during that period. [A detailed discussion of critical service loss duration for industrial and commercial plants and plant restart times is presented in Chapter 7.](#)~~IEEE surveys (see IEEE Committee Reports [B15], [B16], and Patton [B20]) have revealed a wide variation in the minimum or critical service loss duration. Table 2-2 summarizes results for industrial plants, and Table 2- gives results for commercial buildings. It is clear from these tables that careful attention must be paid to choosing the proper interruption definition in any specific reliability evaluation.~~

3.2.3 Service interruption definition

The first step in any electric power system reliability study should be a careful assessment of the power supply quality and continuity required by the loads that are to be served. This assessment should be summarized and expressed in a service interruption definition that can be used in the succeeding steps of the reliability evaluation procedure. The interruption definition specifies, in general, the reduced voltage level (voltage dip or sag) together with the minimum duration of such a reduced voltage period that results in substantial degradation or complete loss of function of the load or process being served. Frequently, reliability studies are conducted on a continuity basis in which case interruption definitions reduce to a minimum duration specification with voltage assumed to be zero during the interruption, which will be assumed in the reliability analysis presented in this chapter. A method for calculating the magnitude of voltage sags is given in Chapter 7. Sags can be caused by faults elsewhere on the power system.

¹[Information on references can be found in 3.6.](#)

3.2.4 Data needed for system reliability evaluations

The data needed for quantitative evaluations of system reliability depend to some extent on the nature of the system being studied and the detail of the study. In general, however, data on the performance of individual components together with the times required to perform repair and/or replacement actions and the times for various switching operations are summarized as follows:

- a) Failure rates (forced outage rates) associated with different modes of component failure
- b) Expected (average) time to repair or replace failed component
- c) Scheduled (maintenance) outage rate of component
- d) Expected (average) duration of a scheduled outage event

The needed manual or automatic switching time data include the following:

- 1) Expected times to open and close a circuit breaker
- 2) Expected times to open and close a disconnect or transfer switch
- 3) Expected time to replace a fuse link
- 4) Expected times to perform such emergency operations

Switching times should be estimated for the system being studied based on experience, engineering judgment, and anticipated operating practice.

If possible, component data should be based on the historical performance of components in the same environment as those in the proposed system being studied. The reliability surveys conducted by the Power Systems Reliability Subcommittee and the U.S. Army Corps of Engineers Power Reliability Enhancement Program (PREP) (reliability data contained in Chapter 10) provide a source of component data when such site-specific data are not available. [Chapter 11 provides a framework for collecting reliability data.](#)

3.2.5 Method for system reliability evaluation

[There are many computer reliability methodologies available today for analyzing complex industrial and commercial power system configurations.](#) The methods for system reliability evaluation have evolved over a number of years (Dickenson et al. [B6], Feduccia and Klion [B9], Patton et al. [B27], Wells [B34], and Love [B25]).² The minimal cut-set method will be used [in the analysis of various](#) electric power distribution systems. The method is systematic and straightforward and lends itself to either manual or computer computation. An important feature of the method is that system weak points can be readily identified, both numerically and non-numerically, thereby focusing design attention on those sections or components of the system that contribute most to service unreliability.

[One of the main benefits of a reliability and availability analysis is that a disciplined look is taken at the alternative choices in the design of the power distribution system. By using published reliability data collected by a technical society from industrial plants, the best possible attempt is made to use historical experience to aid in the design of the new system.](#)

~~See Chapter 8 for a derivation of the minimal cut set method.~~

~~The procedure for system reliability evaluation is outlined as follows:~~

- ~~a) Assess the service reliability requirements of the loads and processes that are to be supplied and determine the appropriate service interruption definition or definitions.~~

- b) Perform a failure modes and effects analysis (FMEA) identifying and listing those component failures and combinations of component failures that result in service interruptions and that constitute minimal cut-sets of the system.
- c) Compute the interruption frequency contribution, the expected interruption duration, and the probability of each of the minimal cut-sets of step b).
- d) Combine the results of step c) to produce system reliability indexes. These steps will be discussed in more detail in that following subclauses.

2.1.8 Failure modes and effects analysis (FMEA)

The FMEA for power distribution systems amounts to the determination and listing of those component outage events or combinations of component outages that result in an interruption of service at the load point being studied according to the interruption definition that has been adopted. This analysis must be made in consideration of the different types and modes of outages that components may exhibit and the reaction of the system's protection scheme to these events.

The primary result of the FMEA as far as quantitative reliability evaluation is concerned is the list of minimal cut-sets it produces. The use of the minimal cut-sets in the calculation of system reliability indexes is described in Chapter 3 of this book. A minimal cut-set is defined to be a set of components that, if removed from the system, results in loss of continuity to the load point being investigated and that does not contain as a subset any set of components that is itself a cut-set of the system. In the present context, the components in a cut-set are just those components whose overlapping outage results in an interruption according to the interruption definition adopted.

An important nonquantitative benefit of the FMEA is the thorough and systematic thought process and investigation that it requires. Often weak points in system design will be identified before any quantitative reliability indexes are computed. Thus, the FMEA is a useful reliability design tool even in the absence of the data needed for quantitative evaluation.

The FMEA and the determination of minimal cut sets are most efficiently conducted by considering first the effects of outages of single components and then the effects of overlapping outages of increasing numbers of components. Those cut-sets containing a single component are termed *first-order cut-sets*. Similarly, cut-sets containing two components are termed *second-order cut-sets*, etc. In theory the FMEA should continue until all the minimal cut-sets of the system have been found. In practice, however, the FMEA can be terminated earlier, since high-order cut-sets have low probability compared to lower-order cut-sets. A good rule of thumb is to determine minimal cut-sets up to order $n + 1$ where n is the lowest order minimal cut-set of the system. Since most power distribution systems have at least some first-order minimal cut-sets, the analysis can usually be terminated after the second-order minimal cut-sets have been found.

2.1.9 Computation of quantitative reliability indexes

The list of minimal cut-sets obtained from the FMEA is used to compute system reliability indexes. Since the occurrence of any cut-set will result in system failure, these cut-sets can be regarded as acting in series. The failure frequency and average outage duration can therefore be computed using Equations (2-1) and (2-2):

$$f_s = \text{System interruption frequency} = \sum_i f_{cs_i}$$

$$\mu_s = \text{System expected interruption duration} =$$

is the frequency of cut-set event i ; and

is the expected duration of cut-set event i .

NOTE—These are approximate formulas and should only be used when the various less than 0.01.

It can be seen from Equations (2-1) and (2-2) that, once the frequency and duration of the various cut sets are known, the load point interruption frequency and duration can be easily computed. Since the various cut set events are not mutually exclusive, Equation (2-1) is an upper bound on the frequency of system failure. Assuming, however, that the time a component spends on outage is very small compared to the time it is operating satisfactorily, Equations (2-1) and (2-2) give results close to the exact values. A later section gives equations for computing the frequency and duration for various types of outage events.

2.1.10 Component failure modes

Distribution system components, such as lines, transformers, and circuit breakers, are subject to a variety of failure modes that, in general, have different impacts on system reliability performance. For system reliability evaluation purposes, it is useful to categorize system components as switching devices or nonswitching devices. First, consider nonswitching devices such as lines or transformers. The important modes of failure are those events that cause the component to be unable to fulfill its current-carrying function, generally due to a fault and subsequent isolation of the faulted component by a protective device. Such failure modes can be modeled in system reliability calculations through the use of permanent forced outage rates and transient forced outage rates, where

λ is the permanent forced outage rate of the component = rate of occurrence of forced outages in which the component is damaged and cannot be restored to service until repair or replacement has been completed; and

λ' is the transient forced outage rate of component = rate of occurrence of forced outages in which the component is undamaged and can be immediately restored to service.

NOTE—A forced outage is defined as “an outage (failure) that cannot be deferred.”

Now consider the failure modes of protection systems and of switching devices, such as circuit breakers. In contrast to the components described above whose only function is carrying current (a continuously required function), protection systems and switching devices generally have both continuously required and response functions. The inability to perform a continuously required function, such as current carrying, will immediately impact system performance while the inability to perform a response function, such as tripping open on command, will be manifested only when the response is required.

Some of the more important failure modes of protection systems and switching devices, and the parameters used to model these failure modes in reliability calculations are summarized as follows:

2.1.10.1 Continuous functions

- a) Component short circuit resulting in operation of backup protective devices. The modeling parameter is λ , which is the rate of occurrence of such short-circuit events.
- b) Switching device opening without the proper command. The modeling parameter is λ_{FO} , which is the rate of occurrence of such events given that the device is closed.
- c) Switching device closing without the proper command. The modeling parameter is λ_{FC} , which is the rate of occurrence of such events given that the device is open.