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

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Power System Technologies Committee
of the
IEEE Industry Applications Society

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Foreword

(This Foreword is not a part of IEEE Std 493-1980, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems.)

The design of reliable industrial and commercial power systems is of considerable interest to many people. Prior to 1962 a qualitative viewpoint was taken when attempting to achieve this objective. The need for a quantitative approach was first recognized in the early 1960s when a small group of pioneers led by W.H. Dickinson organized an extensive AIEE survey of the reliability of electric equipment in industrial plants. The survey of AIEE taken in 1962 was followed by several IEEE reliability surveys which were published during 1973 through 1979.

Tutorial reliability sessions on the design of industrial and commercial power systems were conducted at the 1971 and 1976 IEEE Industry and Commercial Power Systems Technical Conferences. A need has existed for some time that the pertinent tutorial reliability material, equipment reliability data, and cost of power outage data be assembled into a single book that could be useful in the design of reliable industrial and commercial power systems.

Comments are invited on this recommended practice and also suggestions for additional material. These comments and suggestions should be addressed to:

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This recommended practice was prepared by a working group of the Power Systems Reliability Subcommittee, Power Systems Support Committee, Industrial Power Systems Department of the IEEE Industry Application Society.

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1. Introduction

1.1 Objectives and Scope. The objective of this book is to present the fundamentals of reliability analysis as it applies to the planning and design of industrial and commercial electric power distribution systems. The text material is primarily directed toward consulting plant electrical engineers.

The design of reliable industrial and commercial power distribution systems is important because of the high costs associated with power outages. There is a need to be able to consider the cost of power outages when making design decisions for new power distribution systems and to be able to make quantitative cost versus reliability tradeoff studies. The lack of credible data concerning equipment reliability and the cost of power outages has hindered engineers in making such studies.

The authors of this book have attempted to provide sufficient information so that reliability analyses can be performed on power systems without need for cross references to other texts. Included are:

(1) Basic concepts of reliability anal-

ysis by probability methods

(2) Fundamentals of power system reliability evaluation

(3) Economic evaluation of reliability

(4) Cost of power outage data

(5) Equipment reliability data

(6) Examples of reliability analysis

In addition, discussion and information are provided on:

(1) Emergency and standby power

(2) Electrical preventive maintenance

(3) Evaluating and improving reliability of existing plant

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 *first cost* of the system. The material in this book should enable engineers to make more use of quantitative cost versus reliability tradeoff studies during the design of industrial and commercial power systems.

1.2 IEEE Reliability Surveys of Industrial Plants. From 1973 through 1979 the Power Systems Reliability Subcommittee of the Power Systems Support Committee, Industrial Power Systems Department, 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. The results from these surveys have been published in nine IEEE committee reports. The most important results from these surveys are summarized in Chapters 2, 3 and 5 of this book. In addition, the nine IEEE committee reports are reprinted in Appendixes A, B, C, D, and E.

The IEEE survey reliability data 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 a power distribution system and can provide a basis for quantitative cost comparisons between alternate designs.

1.3 How to Use This Book. This book is primarily directed toward consulting engineers and plant electrical engineers and covers the fundamentals of reliability analysis as it applies to the planning and design of industrial and commercial electric power distribution systems. The methods of reliability analysis 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, Table 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 six examples using these methods of analysis. These examples cover some of the most common decisions that engineers are facing when designing a power distribution system. Some discussion on the limitations of reliability and availability predictions are given 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.

2. Planning and Design

2.1 Fundamentals of Power System Reliability Evaluation

2.1.1 Reliability Evaluation Fundamentals. Fundamentals necessary for a quantitative reliability evaluation in electric power systems include definitions of basic terms, discussions of useful measures of system reliability and the basic data needed to compute these indexes, and a description of the procedure for system reliability analysis including computation of quantitative reliability indexes.

2.1.2 Power System Design Considerations. An important aspect of power system design involves consideration of the service reliability requirements of loads which are to be supplied and the service reliability which will be provided by any proposed system. System reliability assessment and evaluation methods based on probability theory which 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 which 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.

2.1.3 Definitions. The definitions presented here include those used in the survey of the reliability of electric equipment in industrial plants.[1]¹ The definitions presented are not exhaustive, but do provide much of the required nomenclature for discussions of power system reliability.

availability. This term may apply either to the performance of individual components or to that of a system. Availability is defined to be the long-term average

¹ Numbers in brackets refer to the references listed in 2.5.

fraction of time that a component or system is in service 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.

component. A piece of equipment, a line or circuit, or a section of a line or circuit, or a group of items which is viewed as an entity for purposes of reliability evaluation.

expected interruption duration. The expected, or average, duration of a single load interruption event.

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

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

- (1) Partial or complete plant shutdown, or below-standard plant operation
- (2) Unacceptable performance of user's equipment
- (3) Operation of the electrical protective relaying or emergency operation of the plant electrical system
- (4) Deenergization of any electric circuit or equipment

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

- (1) A power interruption or loss of service
- (2) A deviation from normal voltage or frequency of sufficient magnitude or duration

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.

failure rate (forced outage rate). The mean number of failures of a component per unit exposure time. Usually exposure time is expressed in years and failure rate is given in failures per year.

forced unavailability. The long-term average fraction of time that a component or system is out of service due to failures.

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

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

outage. The state of a component or system when it is not available to properly perform its intended function.

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 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. It is not the time required to restore service to a load by putting alternate circuits into operation. It includes time for diagnosing the trouble, locating the failed component, waiting for parts, repairing or replacing, testing, and restoring the component to service. The terms *repair time* and *forced outage duration* are often used synonymously.

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.

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.

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

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: throw-over 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.

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

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. Mathematically, unavailability = $(1 - \text{availability})$.

2.1.4 System Reliability Indexes. The basic system reliability indexes [2], [3], which have proven most useful and meaningful in power distribution system design are:

- (1) Load interruption frequency
- (2) Expected duration of load interruption events

These indexes can be readily computed using the methods which will be described later. The two basic indexes of interruption frequency and expected in-

terruption duration can be used to compute other indexes which are also useful:

- (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 demanded, 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.

2.1.5 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 various switching operations are required.

System component data which are generally required are summarized as follows:

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

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 [1], [4] provide a source of component data when such specific data are not available. These data have been summarized in Chapter 3.

The needed switching time data include:

- (1) Expected times to open and close a circuit breaker
- (2) Expected times to open and close a disconnect or throwover switch
- (3) Expected time to replace a fuse link
- (4) Expected times to perform such emergency operations as cutting in clear, installing jumpers, etc

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

2.1.6 Method for System Reliability Evaluation. The method for system reliability evaluation which is recommended and presented here has evolved over a number of years [2], [5], [8]. The method, called the *minimal-cut-set method*, is believed to be particularly well suited to the study and analysis of electric power distribution systems as found in industrial plants and commercial buildings. 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 of the system that contribute most to service unreliability. See Chapter 8 for a derivation of the *minimal cut-set*-method.

The procedure for system reliability evaluation is outlined as follows:

- (1) Assess the service reliability requirements of the loads and processes which are to be supplied and determine

the appropriate service interruption definition or definitions.

- (2) Perform a failure modes and effects analysis identifying and listing those component failures and combinations of component failures that result in service interruptions and which constitute minimal cut-sets of the system.

- (3) Compute the interruption frequency contribution, the expected interruption duration, and the probability of each of the minimal cut-sets of step (2).

- (4) Combine the results of step (3) to produce system reliability indexes.

These steps will be discussed in more detail in the sections that follow.

2.1.7 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 which are to be served. This assessment should be summarized and expressed in a service interruption definition which can be used in the succeeding steps of the reliability evaluation procedure. The interruption definition specifies, in general, the reduced voltage level (voltage dip) together with the minimum duration of such a reduced voltage period which 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.

A further discussion of interruption definitions together with examples of such definitions is given in 7.1.2.

2.1.8 Failure Modes and Effects Analysis. Failure modes and effects analysis (FMEA) for power distribution systems amounts to the determination and listing of those component outage events or

combinations of component outages which result in an interruption of service at the load point being studied according to the interruption definition which has been adopted. This analysis must be made considering the different types and modes of outages which components may exhibit and the reaction of the system's protection scheme to these events. Component outages may be categorized as:

- (1) Forced outages or failures
- (2) Scheduled or maintenance outages
- (3) Overload outages

Forced outages or failures may be further categorized as:

- (1) Permanent forced outages
- (2) Transient forced outages

Permanent forced outages require repair or replacement of the failed component before it can be restored to service, while transient forced outages imply no permanent damage to the component, thus permitting its restoration to service by a simple reclosing or refusing operation. Additionally, component failures may be categorized by physical mode or type of failure. This type of failure categorization is important for circuit breakers and other switching devices where failure modes such as the following are possible and have varying impacts on system performance:

- (1) Faulted, must be cleared by back-up devices
- (2) Fails to trip when required
- (3) Trips falsely
- (4) Fails to re-close when required

The primary result of the failure modes and effects analysis (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 which, if removed from the system, results in loss of continuity to the load point being investigated and which does not contain as a subset any set of components which 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 non quantitative benefit of the failure modes and effects analysis (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 failure modes and effects analysis (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 is 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. Computation of reliability indexes may proceed once the minimal cut-sets of the system have been found. The first step is to compute the frequency, expected duration, and expected down time per year of each minimal cut-set. Note that the expected down time per year is just the product of the frequency expressed in terms of events per year and the expected duration. If the expected duration is expressed in years, the expected down time will have the unit of years per year and may be regarded as the relative proportion of time or the probability the system is down due to the minimal cut-set in question. More commonly the expected duration is expressed in hours, and the expected down time has the unit of hours per year.

Approximate expressions for the frequency and expected duration of the most commonly considered interruption events associated with first-, second- and third-order minimal cut-sets are given in Table 1. These are discussed in more detail in Chapter 8.

Note that expressions are given for forced outages (failures) and for forced outages overlapping a maintenance outage. The basic assumptions made in deriving the expressions of Table 1 are as follows:

(1) Component failure and repair events are statistically independent.

(2) Component *up* times are much larger than *down* times. That is, the probability that a component is up is much larger than the probability that it is down.

(3) Components are not taken out of service for maintenance or other deferrable work if other components are on forced outage, but forced outages of components may occur during the scheduled outage of a component.

(4) Components which act in parallel to carry load are fully redundant. That is, any one component of the parallel combination is capable of carrying the entire load of the parallel combination without overload. (Methods for treating overload outages are given in 2.1.12).

Once the frequencies and expected durations have been computed for each minimal cut-set, the system reliability indexes at the load point in question are determined.

$$\begin{aligned} f_s &= \text{interruption frequency} \\ &= \sum_{\substack{\text{min} \\ \text{cut-sets}}} f_{cs_i} \end{aligned}$$

$$\begin{aligned} r_s &= \text{expected interruption duration} \\ &= \sum_{\substack{\text{min} \\ \text{cut-sets}}} f_{cs_i} r_{cs_i} / f_s \end{aligned}$$

$$f_s r_s = \text{total interruption time per time period}$$

2.1.10 Example: Sample System Evaluation. The reliability evaluation method which has been described will now be illustrated through a simple example. More detailed examples using typical data are given in Chapter 7.

Consider the simple system of Fig 1. Here, for the sake of simplicity, only the components labeled 1, 2, and 3 will be considered fallible, and only permanent forced outages and scheduled outages

Table 1
Frequency and Expected Duration Expressions for Interruptions
Associated with Minimal Cut-Sets

Forced Outages		
<i>First-Order Minimal Cut-Set</i>	<i>Second-Order Minimal Cut-Set</i>	<i>Third-Order Minimal Cut-Set</i>
$f_{cs} = \lambda_i$	$f_{cs} = \lambda_i \lambda_j (r_i + r_j)$	$f_{cs} = \lambda_i \lambda_j \lambda_k (r_i r_j + r_i r_k + r_j r_k)$
$r_{cs} = r_i$	$r_{cs} = r_i r_j / (r_i + r_j)$	$r_{cs} = r_i r_j r_k / (r_i r_j + r_i r_k + r_j r_k)$

Forced Outages Overlapping Scheduled Outage

Second-Order Minimal Cut-Set

$$r_{cs} = \left[\lambda_i \lambda_j' \left(\frac{r_i' r_j'}{r_i' + r_j'} \right) + \lambda_j' \lambda_i' r_j' \left(\frac{r_j' r_i'}{r_j' + r_i'} \right) \right] / f_{cs}$$

Symbols:

- f_{cs} = frequency of cut-set event
 r_{cs} = expected duration of cut-set event
 λ_i = forced outage rate of i th component
 λ_i' = scheduled outage rate of i th component
 r_i = expected repair or replacement time of i th component
 r_i' = expected scheduled outage duration of i th component

Third-Order Minimal Cut-Set

$$f_{cs} = A + B + C$$

$$r_{cs} = \left[A \left(\frac{r_i' r_j' r_k}{r_i' r_j + r_i' r_k + r_j r_k} \right) + B \left(\frac{r_j' r_i' r_k}{r_j' r_i + r_j' r_k + r_i r_k} \right) + C \left(\frac{r_k' r_i' r_j}{r_k' r_i + r_k' r_j + r_i r_j} \right) \right] / f_{cs}$$

where:

$$A = \lambda_i' \lambda_j \lambda_k r_i' \left(\frac{r_i' r_j}{r_i' + r_j} + \frac{r_i' r_k}{r_i' + r_k} \right)$$

$$B = \lambda_j' \lambda_i \lambda_k r_j' \left(\frac{r_j' r_i}{r_j' + r_i} + \frac{r_j' r_k}{r_j' + r_k} \right)$$

$$C = \lambda_k' \lambda_i \lambda_j r_k' \left(\frac{r_k' r_i}{r_k' + r_i} + \frac{r_k' r_j}{r_k' + r_j} \right)$$

Note 1: The time units of r and λ in expressions for f_{cs} must be the same.

Note 2: If service can be restored to the affected load point by a switching operation, set r_{cs} = expected switching time. Note that this assumes that switching times are short compared to repair or replacement times.

Fig 1
Sample System

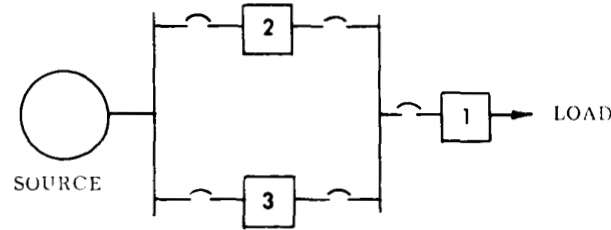


Table 2
Sample System Evaluation

Minimal Cut-Sets	f_{cs}	r_{cs}	$f_{cs}r_{cs}$
Forced Outages:			
Component 1	λ_1	r_1	$\lambda_1 r_1$
Component 2/Component 3	$\lambda_3 \lambda_2 (r_3 + r_2)$	$r_3 r_2 (r_3 + r_2)$	$\lambda_3 \lambda_2 r_3 r_2$
Forced/Scheduled Outages:			
	$\left[\lambda_3 \lambda_2 r_3' \left(\frac{r_3' r_2}{r_3' + r_2} \right) + \lambda_2 \lambda_3 r_2' \left(\frac{r_2' r_3}{r_2' + r_3} \right) \right]$		$\lambda_3 \lambda_2 r_3' \left(\frac{r_3' r_2}{r_3' + r_2} \right)$
Component 2/Component 3	$\lambda_3 \lambda_2 r_3' + \lambda_2 \lambda_3 r_2'$	$\lambda_3 \lambda_2 r_3' + \lambda_2 \lambda_3 r_2'$	$+ \lambda_2 \lambda_3 r_2' \left(\frac{r_2' r_3}{r_2' + r_3} \right)$
Totals	$\sum f_{cs}$		$\sum f_{cs} r_{cs}$
System indices:			
	$f_s = \sum f_{cs}$		
	$r_s' = \sum f_{cs} r_{cs} / f_s$		

will be assumed possible. Additionally, scheduled outages of component 1 which would result in interruptions to the load are assumed to be taken during periods of plant maintenance shutdown and are not treated in the reliability analysis. All circuit breakers are assumed to be normally closed and are coordinated to minimize system disruption due to a component failure.

The load is assumed not to be sensitive to voltage dips limited to the time required to clear a fault, but any loss of continuity from source to load constitutes an interruption to the load. Using this definition of an interruption, the minimal cut-sets of the system are shown in Table 2. Also shown in Table 2 are the expressions needed for the calculation of the system reliability indexes.

2.1.11 Post Fault Switching. Power systems are frequently designed with protective and switching schemes that allow restoration of service through some switching action following one or more component failures. The key point in such cases is that the duration of the interruption event is the time to perform the switching operation rather than the

time to repair or replace failed components. Thus when computing the frequency and duration of a system interruption event (minimal cut-set), the frequency is computed as outlined in Tables 1 and 2, but the duration becomes simply the switching time (assuming that the switching time is short compared to the repair or replacement time).

The procedure is most easily described through use of a simple example. Consider the system of Fig 2 in which power is supplied from a source to a load over two parallel circuits with the sectionalizing scheme shown. Assume for the purposes of the example that only the circuits are subject to failure and that each circuit has a failure rate of λ_i and an average repair time of r_i . Assume further that the sectionalizing switches at the load point can be opened in a time t_s to isolate a faulty circuit and that all circuit breakers and switches are normally closed.

If the definition of system failure is loss of continuity from source to load, the general reliability evaluation procedure yields the results given in Table 3.

Table 3
Sample System Evaluation
Considering Post-Fault Switching

Minimal-Cut	Frequency	Duration	Probability
Failure of circuit 1	λ_1	t_s	$\lambda_1 t_s$
Failure of circuit 2	λ_2	t_s	$\lambda_2 t_s$
Failure of both circuits	$\lambda_1 \lambda_2 (r_1 + r_2)$	$\frac{r_1 r_2}{(r_1 + r_2)}$	$\lambda_1 \lambda_2 r_1 r_2$

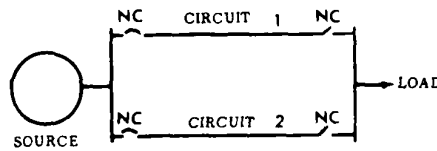


Fig 2
Example of Post-Fault Switching

Note that *failure of both circuits* is not, strictly speaking, a minimal cut-set since failure of either circuit alone constitutes a system failure and load interruption. The justification for including *failure of both circuits* is the desire to give frequency, duration, and probability information on both short-duration interruptions which are terminated by switching actions and long-duration interruptions which are terminated by repair or replacement efforts. In the event that load sensitivity is such that differences in power supply interruption durations are not important, *failure of both circuits* could have been omitted and only the frequency of minimal cut-sets calculated. In general system failure, frequency and probability are obtained by summing the frequency and probability columns, respectively. If it is desired to separate short- and long-duration interruption performance, these summations are carried out with due regard to the average durations of the various cut-sets. Average interruption duration is given by system failure probability divided by system failure frequency.

2.1.12 Incomplete Redundancy. A common method of improving the reliability performance of a system is through component redundancy, for example, more than one transformer in a substation. Typically, each component of the redundant set has sufficient capacity, perhaps based on an emergency rating, to carry the peak load that the system may be asked to deliver. Such full redundancy is effective in improving system reliability performance but is usually quite expensive. If the load of the system is variable, the opportunity exists to cut costs by reducing the capacity of redundant components to levels less than that required to carry system peak load. Such component capacity reductions admit the possibility that one component of the redundant set might be called upon to carry system peak load and would thereby suffer an overload outage. An overload outage might result in an actual interruption of load or perhaps only some loss of life in the overloaded component, depending on the protection scheme in service.

A method exists [9], [10] for computing the frequency, average duration,

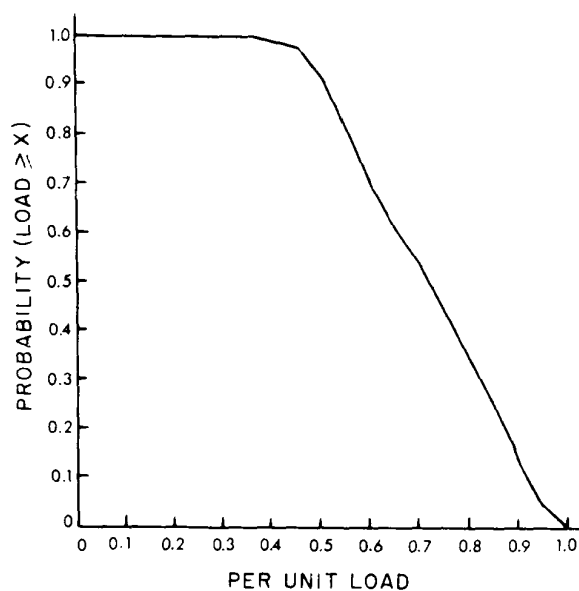


Fig 3
Typical Load-Duration Characteristic

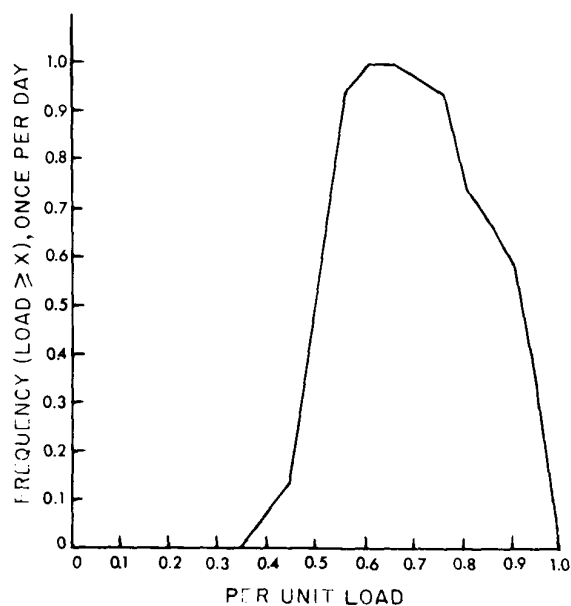


Fig 4
Typical Load-Frequency Characteristic

and probability of overload outage events as a function of component capacities and load characteristics. This method, which is compatible with the general reliability evaluation procedure outlined earlier, can be used to evaluate the cost-reliability tradeoffs of incomplete redundancy. The method is briefly presented hereafter.

Consider a system possessing incomplete redundancy, and consider the forced outage of some set i of the components of this system. Let the frequency and probability of this forced outage event be f_i and P_i . Then the frequency, probability, and average duration of overloading events that are precipitated by loss of the components in set i are given approximately by:

$$f_{OL_i} = f_i \cdot P \text{ (load } \geq \text{ capacity of remaining components)}$$

$$+ P_i \cdot f \text{ (load } \geq \text{ capacity of remaining components)}$$

$$P_{OL_i} = P_i \cdot P \text{ (load } \geq \text{ capacity of remaining components)}$$

$$D_{OL_i} = P_{OL_i} / f_{OL_i}$$

In the above expressions $P \text{ (load } \geq X)$ is called the load-duration characteristic and is simply the probability of proportion of time that the load is greater than or equal to X . A typical load-duration characteristic for utility load is shown in Fig 3. Similarly, $f \text{ (load } \geq X)$ is called the load-frequency characteristic and is the rate with which events (load $\geq X$) occur. A typical load-frequency characteristic is shown in Fig 4. The reader is referred to [10] for additional discussion of the load-duration and load-frequency characteristics.

2.2 Costs of Interruptions; Economic Evaluation of Reliability

2.2.1 Cost of Interruptions Versus Capital Cost. The type and extent of new or rehabilitated electric systems for industrial plants or commercial buildings must carefully balance the costs of anticipated interruptions to electrical service against the capital costs of the systems involved. Each instance requires a separate analysis taking into account special production and occupancy needs. Because of the many variables involved, one of the most difficult items to obtain is the cost of the electrical interruptions.

2.2.1.1 What is an Interruption? Economic evaluation of reliability begins with the establishment of an interruption definition. Such a definition specifies the magnitude of the voltage dip and the minimum duration of such a reduced-voltage period which 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.

IEEE surveys, [12], [13], [14], have revealed a wide variation in the minimum or *critical* service loss duration. Table 4 summarizes results for industrial plants and Table 5 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.

Another important consideration in the economic evaluation of reliability is the time required to restart a plant or process following a power interruption. An IEEE survey [12], (shown in Table 6) indicates that industrial plant restart time following a complete plant shut-

Table 4
Critical Service Loss Duration for
Industrial Plants*

(Maximum length of time an interruption of electrical service will not stop plant production.)

25th Percentile	Median	75th Percentile	Average Plant Outage Time for Equipment Failure Between 1- and 10-Cycle Duration
10.0 cycles	10.0 seconds	15 minutes	1.39 hours

*55 plants in the United States and Canada reporting; all industry.

Table 5
Critical Service Loss Duration for Commercial Buildings*

(Maximum length of time before an interruption to electrical service is considered critical.)

Service Loss Duration Time							
1 cycle %	2 cycles %	8 cycles %	1 second %	5 minutes %	30 minutes %	1 hour %	12 hours %
3	6	9	15	36	64	74	100

*Percentage of buildings with critical service loss for duration less than or equal to time indicated (54 buildings reporting).

down due to a power interruption averages 17.4 hours. The median plant restart time was found to be 4.0 hours. Clearly, specific data on plant or process restart time should be used if possible in any particular evaluation.

Many industrial plants reported that 1 to 10 cycles were considered critical interruption time, as compared to 1.39 h, required for startup, (plant outage time being considered equal to plant startup time). This indicates that the

critical factor must be carefully explored prior to assigning a cost to the interruption. That 15% of the commercial buildings reported the critical service loss duration time to be 1 second or less is probably attributable to the fact that computer installations were involved.

Further data from [12] graphically illustrates the time required to start an industrial plant after an interruption.

Step 1 of the cost analysis thus becomes the selection of the *critical dura-*

Table 6
Plant Restart Time*

(After service is restored following a failure that has caused a complete plant shutdown.)

Average (hours)	Median (hours)
17.4	4.0

*43 plants in the United States and Canada reporting; all industry.

tion time of the outage and the *plant startup* time, including equipment repair or replacement time required because of the interruption.

2.2.1.2 Cost of an Electrical Service Interruption. With the establishment of expected downtime per interruption, costs are assigned to all individual items involved, including but not limited to:

- (1) Value of loss production time less expenses saved (expected restart time is used along with the repair or replacement time)
- (2) Damaged plant equipment
- (3) Spoiled or off-specification product
- (4) Extra maintenance costs
- (5) Cost for repair of failed component

If possible, the cost for each interruption of service should be expressed in a short interruption plus an amount of dollar per hour for the total outage time in order to utilize the reliability data and analysis presented.

2.2.1.3 Economic Evaluation of Reliability . There are many methods of varying degrees of complexity for

accomplishing economic evaluations. For quick *order-of-magnitude* or *Is it worth further investigation?* type of evaluations, cost data from [12], [14] can be used. Caution must be exercised however, since these data are very general in nature, and wide variations are possible in individual cases. Some of the more commonly accepted methods for economic analyses are:

- (1) Revenue requirements (RR)
- (2) Return on investment (ROI)
- (3) Life cycle costing (LCC)

It is not the intent to stipulate here the method to be used nor the depth to which each analysis is to be made. These are considered to be the prerogative of the engineer and will depend heavily on management choice and the time available for the analysis. The revenue requirements (RR) method is given in this chapter as an example.

2.2.2 "Order of Magnitude" Cost of Interruptions. IEEE surveys, References [2], [4], presented general data on the cost of interruptions to industrial plants and commercial buildings. The reader is again cautioned that such general data should be used only for "order of magnitude" evaluations where data specific to the system being studied is not available. A review of the reliability data can probably best be used in adjudicating the type of utility company service which should be provided.

The costs based on the kW interrupted and the kWh not delivered to

industrial plants are presented in Tables 7 and 8.

Interruption costs based on kWh not delivered and reflecting the relationship to duration of interruptions for commercial buildings are presented in the Tables 9 and 10.

2.2.3 Economic Analysis of Reliability in Electrical Systems. There are several acceptable methods for accomplishing an economic analysis of the reliability in electric systems. The examples of reliability analysis included in this chapter and Chapter 7 utilize the Revenue Requirements (RR) method. The application of this method as it applied to the analyses of the reliability in Industrial Plant Electrical Systems was presented in Reference part 6 of [2]. Applicable excerpts from this reference are included herein.

2.2.3.1 The Revenue Requirements (RR) Method. Although there are many ways in use to compare alternatives, some of these have defects and

weaknesses, especially when comparing design alternatives in contrast to overall projects. The RR method is “mathematically rigorous and quantitatively correct to the extent permitted by accuracy with which items of cost can be forecast.” [2], [13]

The essence of the RR method is that for each alternative plan being considered, the Minimum Revenue Requirements (MRR) is determined. This means that we find out how much product we must sell to achieve minimum acceptable earnings on the investment involved plus all expenses associated with that investment. These MRRs for alternative plans may be compared directly. The plan having the lowest MRR is the economic choice.

MRR is made up of and equal to (1) variable operating expenses, (2) minimum acceptable earnings, (3) depreciation, (4) income taxes, and (5) fixed operating expenses. These MRRs may be separated into two main parts, one proportional and the other not propor-

Table 7
Average Cost of Power Interruptions for Industrial Plants*

All Plants	\$1.89/kW + \$2.68/kWh
Plants > 1000 kW Max Demand	\$1.05/kW + \$0.94/kWh
Plants < 1000 kW Max Demand	\$4.59/kW + \$8.11/kWh

*41 plants in the United States and Canada reporting—published in 1973.

Table 8
Median Cost of Power Interruptions for Industrial Plants*

All plants	\$0.69/kW + \$0.83/kWh
Plants > 1000 kW Max Demand	\$0.32/kW + \$0.36/kWh
Plants < 1000 kW Max Demand	\$3.68/kW + \$4.42/kWh

*41 plants in the United States and Canada reporting—published in 1973.

Table 9
Average Cost of Power Interruptions for Commercial Buildings

All commercial buildings*	\$7.21/kWh not delivered
Office buildings only	\$8.86/kWh not delivered

*54 buildings in the United States reporting—published in 1975.

Table 10
Cost of Power Interruptions
as a Function of Duration
for Office Buildings (with Computers)*

Power Interruptions	Sample		Cost/Peak kWh Not Delivered Minimum	Average
	Size	Maximum		
15-min duration	14	\$22.22	\$1.88	\$8.89
1-Hour duration	16	\$24.93	\$1.88	\$8.30
Duration > 1-hour	10	\$67.66	\$0.16	\$9.81

*Published in 1975.

tional to investment in the alternative. This may be expressed in an equation:

$$G = X + CF \quad (\text{Eq 1})$$

where

- G = minimum revenue requirements (MRR) to achieve minimum acceptable earnings
- X = nonfixed or variable operating expenses
- C = capital investment
- F = fixed investment charge factor

The last term in Eq 1, the product of C and F includes the items (2), (3), (4), and (5) listed in the preceding paragraph. Equation 1 is now discussed.

X—Variable Expenses. The effect of the failure of a component is to cause an increase in variable expenses. How serious this increase is depends to a great extent on the location of the component in the system and on the type of power distribution system employed. The quality of a component as installed can have a significant effect on the number of failures experienced. A poor quality component installed with poor workmanship and with poor application engineering may greatly increase the number of failures that occur as compared with a high quality component installed with excellent workmanship and sound application engineering.

When a failure does occur, variable expenses are increased in two ways. In the first way, the increase is the result of the failure itself. In the second way, the increase is proportional to the duration of the failure.

Considering the first way, the increased expense due to the failure includes the following:

- (1) Damaged plant equipment
- (2) Spoiled or off-specification product
- (3) Extra maintenance costs
- (4) Costs for repair of the failed component

Considering the second way, plant downtime resulting from failures is made up of the time required to restart the plant, if necessary, plus the time to (1) effect repairs, if it is a radial system, or (2) effect a transfer from the source on which the failure occurred to an energized source.

During plant downtime, production is lost. This lost production is not available for sale, so revenues are lost. However, during plant downtime, some expenses may be saved, such as expenses for material, labor, power, and fuel costs. Therefore, the value of the lost production is the revenues lost, because production stopped less the expenses saved. Some of the variable expenses may vary depending on the duration of plant downtime. For example, if plant downtime is only one hour, perhaps no labor costs are saved. But, if plant downtime exceeds eight hours, labor costs may be saved.

If we assume that the value/hour of variable expenses does not vary with the duration of plant downtime, then the value of lost production can be expressed on a per hour basis, and the total value of lost production is the product of plant downtime in hours and the value of lost production per hour.

It should be noted that both the value of lost production and expenses incurred are proportional to the failure rate. The

total effect on variable expenses, if the value of lost production is a constant on a per hourly basis, may be expressed in an equation.

$$X = \lambda [x_i + (g_p - x_p)(r + s)] \quad (\text{Eq 2})$$

where

- X = variable expenses (\$ per year)
- λ = failures per year or failure rate
- x_i = extra expenses incurred per failure (\$ per failure)
- g_p = revenues lost per hour of plant downtime (\$ per hour)
- x_p = variable expenses saved per hour of plant downtime (\$ per hour)
- r = repair or replacement time after a failure (or transfer time if not radial system), hours
- s = plant startup time after a failure, hours

Assume that

- λ = 0.1 failure per year
- x_i = \$20,000 per failure, extra expenses incurred
- g_p = \$8,000 per hour, revenues lost
- x_p = \$6,000 per hour, expenses saved
- r = 10 hours per failure
- s = 20 hours per failure

Then, variable expenses affected would be:

$$\begin{aligned} X &= (0.1)[\$20,000 \\ &\quad + (\$8,000 - \$6,000)(10 + 20)] \\ &= \$8,000 \text{ per year} \end{aligned}$$

The term g_p represents revenues lost and it is not really an expense. However, it is a negative revenue, and as such has the same effect on the economics as a positive expense item. It is convenient to treat it as though it were an expense.

A failure rate of 0.1 failure per year is equivalent to a mean time between failures of 10 years. Since we are dealing with probability, this is what we can expect, but in a specific case, we might have two failures in one 10 year period and no failures in another 10 year period. But considering many similar cases, we expect to have an average of 0.1 failure per year, with each failure costing an average of \$80,000. This gives an equal average amount per year in the above example of \$8,000.

The point is that even though the actual failures cost \$80,000 each and occur once every 10 years, a given failure is just as likely to occur in any of the 10 years. The equivalent equal annual amount of \$8,000 per year is the average value of one failure in 10 years.

c—Investment. Each different alternative is an industrial plant power distribution system involves different investments. The system requiring the least investment will usually be some form of radial system. By varying the type of construction and the quality of the components in the system, the investment in radial systems can vary widely.

The best method is to find one total investment in each alternative plan. Another common method is to find the incremental investment in all alternatives over a base or least expensive plan. The main reason that the total investment method is preferable, is that in comparing alternatives, the investment is multiplied by an F factor which will be explained later. This factor is

usually the same for alternative plans of the sort being considered here, but this is not necessarily the case.

Using the incremental investment may thus introduce a slight error into the economic comparisons.

F—*Investment Charge Factor*. This discussion of investment charge factor is taken from [2].

The factor *F* includes the following items which are fixed in relation to the investment.

- (1) Minimum acceptable rate of return on investment, allowing for risk
- (2) Income taxes
- (3) Depreciation
- (4) Fixed expenses

An equation to calculate the *F* factor is:

$$F = \left[\frac{(S_c a_L / f_r) - t \bar{d}_t}{1-t} \right] + e \quad (\text{Eq 3})$$

This may also take the following form:

$$F = \bar{r} + \bar{d} + \bar{t} + e \quad (\text{Eq 4})$$

where

$a_n = R + d_n$, amortization factor or leveling factor

$d_n = R/(S_n - 1)$, sinking fund factor

$S_n = (1 + R)^n$, growth factor or future value factor

n = period of years, such as c or L

c = years prior to startup that an investment is made

L = life of investment years

R = minimum acceptable earnings per \$ of C , investment

f_r = probability of success or risk adjustment factor

t = income taxes per \$ of C , investment

$\bar{d}_t$ = income tax depreciation, levelized per \$ of C , investment = $1/L$, $d_t = 1L$

e = fixed expenses per \$ of C , investment

$\bar{r}$ = levelized return on investment per \$ of C , investment

$\bar{d}$ = levelized depreciation on investment per \$ of C , investment

$\bar{t}$ = levelized income taxes on investment per \$ of C , investment

Assume

L = 20 years, life of investment

c = 1 year

R = 0.15, minimum acceptable rate of return

f_r = 1, risk adjustment factor

t = 0.5, income tax rate

$\bar{d}_t = \frac{1}{L} = 0.05$

$e = 0.0825$

Then

$S_c = (1+R)^c = (1+0.15)^1 = 1.15$

$S_L = (1+R)^L = (1+0.15)^{20} = 16.37$

$d_L = R/(S_L - 1) = 0.15/(16.37 - 1) = 0.0098$

$a_L = R + d_L = 0.15 + 0.0098 = 0.1598$

Substituting into Eq 3 to calculate the F factor, we get:

$$F = \left[\frac{\frac{(1.15)(0.1598)}{1.0} - (0.5)(0.05)}{(1-0.5)} \right] + 0.0825 = 0.4 \quad (\text{Eq 5})$$

All the assumed values are believed to be typical for the average electric distribution system, except the value of $e = 0.0825$. This latter value was arbitrarily assumed to make R round out to 0.4. The term e covers such items as insurance, property taxes, and fixed maintenance costs. A typical value is probably less than 0.0825.

It is believed that a typical value for minimum acceptable return on investment in many industrial plants is 15 percent, that is, $R = 0.15$. The company average rate of return, based on either past history or anticipated results, is a measure of what R should be. In plants of higher risk than the average, the risk adjustment factor, f_r , should probably be less than 1. However, company management determines what the value of R should be.

The value of F can be calculated from Eq 3 using a log log slide rule. In [14], tabular values are given for the factors S_n and a_n for various rates of return and plant lifes.

2.2.3.2 Steps for Economic Comparisons.

1. Prepare one-line diagrams of alternative plans and assign failure rates, repair times, and investment in each component, and determine the total investment C , in each plan.

2. Determine X , the increased variable expense for each plan as the sum of the value of lost production and the extra variable expenses incurred.

3. Determine F , the fixed investment charge factor, F from Eq 3.

4. Calculate $G = X + CF$, the minimum revenue requirements G of each plan. Eq 1.

5. Select as the economic choice the plan having the lowest value of G .

2.2.3.3 Conclusions. A technique has been presented for the economic evaluation of power system reliability. The method of determining the failure rates and repair times of different alternatives is not covered here. Additional information relative to the RR Method is included in [13].

2.2.4 Examples. Examples of electric systems with varying degrees of reliability (availability), together with fixed and variable costs are given in Chapter 7.

2.3 Cost of Scheduled Electrical Preventive Maintenance

It is always appropriate to consider in the economic evaluation of reliability the costs for scheduled electrical preventive maintenance. Sometimes these costs are large enough to make it desirable to analyze them separately when comparing alternative designs of industrial power systems. The *Revenue Requirements Method* described in 2.2.3 includes a term called the Investment Charge Factor, F which is given by Eq 3 in 2.2.3 and includes e the fixed yearly expenses e (as a percentage of the capital investment) are attributed to scheduled electrical preventive maintenance, insurance, property taxes, etc. Since the yearly average costs for scheduled electrical preventive maintenance may not be the same percentage of investment for every component within the industrial power system, a separate more detailed look is often taken at these costs for each component.

Scheduled electrical preventive maintenance has two major cost elements; labor effort and spare parts consumed. These costs are often expressed on an average yearly basis so as to be usable with the "Revenue Requirements Method" when an economic evaluation is made. These data are needed for each different type of component used in the industrial power system and can be compiled for each component as follows:

- (1) Labor Costs in manhours per component per year
- (2) Cost of spare parts consumed in dollars per component per year
- (3) Labor rate in dollars per manhour

If, for example, a component is only maintained once every three years, then its maintenance costs should be divided by three in order to determine the average yearly maintenance cost. The labor rate used probably should only include the overhead costs associated with the storage of spare parts, direct supervision of the maintenance, and costs for necessary test equipment. The labor costs in dollars per component per year can be calculated by multiplying items (1) and (3) together; the result can then be added to item (2) to get the total average yearly costs that are attributable to scheduled electrical preventive maintenance.

Data thus collected can become obsolete at a later date due to inflation which can result in changing the labor rate used and also the average yearly cost of spare parts consumed. But the data for labor in manhours per component per year does not become obsolete due to inflation. Some engineers have chosen to use their labor rate to convert their average yearly cost data for spare parts consumed into average yearly "equivalent manhours" data.

This is then added to the labor manhours data to get total equivalent manhours per component per year that includes both the labor cost and the cost of spare parts consumed. The use of equivalent manhours for cost data instead of dollars has two advantages:

- (1) The equivalent manhours data do not become obsolete due to inflation
- (2) The equivalent manhours data can be considered an international currency. The data are not affected by changing exchange rates between the currencies or different countries. This enables the cost data to be compared with studies from other countries.

No component data are included in this book on the cost of scheduled electrical preventive maintenance. It would be desirable to have such data for all of the electrical equipment categories listed in Table 11 of Chapter 3. It would then be possible to consider the cost of scheduled electrical preventive maintenance in design decisions of the industrial power system by adding this into the Minimum "Revenue Requirements Method."

2.4 Effect of Scheduled Electrical Preventive Maintenance on Failure Rate

One of the important total operating cost decisions made by the management of an industrial plant is how much money to spend for scheduled electrical preventive maintenance. The amount of maintenance performed on a component can affect its failure rate. Very little quantitative data have been collected and published on this subject. Yet this is an important factor when attempting to study the total owning costs of a complete power system. If maintenance

Table 11
Summary of All-Industry Equipment Failure Rate and Equipment Outage Duration
Data for 60 Equipment Categories Containing Eight or More Failures
(See Tables 4 through 19 in Appendix A for additional details)

Equipment	Equipment Subclass	Failure Rate (failures per unit-year)	Actual Hours of Downtime Per Failure	
			Industry Average	Median Plant Average
Transformers	Liquid filled — all	0.0041	529.0	219.0
	601–15 000 V — all sizes	0.0030	*174.0	49.0
	300–750 kVA	0.0037	61.0	10.7
	751–2499 kVA	0.0025	217.0	64.0
	2500 kVA and up	0.0032	216.0	60.0
	Above 15 000 V	0.0130	*1076.0	1260.0
Circuit breakers	Dry type: 0–15 000 V	0.0036	153.0	28.0
	Rectifier: Above 600 V	0.0298	380.0	80.0
	Fixed type (including molded case) — all	0.0052	5.8	4.0
	0–600 V — all sizes	0.0044	4.7	4.0
	0–600 A	0.0035	2.2	1.0
	Above 600 A	0.0096	9.6	8.0
	Above 600 V	0.0176	10.6	3.8
	Metalclad drawout — all	0.0030	129.0	7.6
	0–600 V — all sizes	0.0027	*147.0	4.0
	0–600 A	0.0023	3.2	1.0
	Above 600 A	0.0030	232.0	5.0
	Above 600 V	0.0036	*109.0	168.0
Motor starters	Contact type: 0–600 V	0.0139	65.1	24.5
Motors	Contact type: 601–15 000 V	0.0153	284.0	16.0
	Induction: 0–600 V	0.0109	*114.0	18.3
	Induction: 601–15 000 V	0.0404	*76.0	91.5
	Synchronous: 0–600 V	0.0007	35.3	35.3
	Synchronous: 601–15 000 V	0.0318	*175.0	153.0
Generators	Direct current — all	0.0556	37.5	16.2
	Steam turbine driven	0.032	165.0	66.5
	Gas turbine driven	0.638	23.1	92.0
Disconnect switches	Enclosed	0.0061	3.6	2.8
Switchgear bus — indoor and outdoor (Unit = number of connected circuit breakers or in- strument transformer compartments)	Insulated: 601–15 000 V**	0.00170	261.0	26.8
	Bare: 0–600 V**	0.00034	550.0	24.0
	Bare: Above 600 V**	0.00063	17.3	13.0
Bus duct — indoor and outdoor (Unit = 1 circuit ft)	All voltages	0.000125	128.0	9.5
Open wire (Unit = 1000 circuit ft)	0–15 000 V	0.0189	42.5	4.0
	Above 15 000 V	0.0075	17.5	12.0
Cable — all types of insulation (Unit = 1000 circuit ft)	Above ground and aerial			
	0–600 V	0.00141	457.0	10.5
	601–15 000 V — all	0.01410	*40.4	6.9
	In trays above ground	0.00923	8.9	8.0
	In conduit above ground	0.04918	140.0	47.5
	Aerial cable	0.01437	31.6	5.3

Table 11 (Continued)

Equipment	Equipment Subclass	Failure Rate (failures per unit-year)	Actual Hours of Downtime per Failure	
			Industry Average	Median Plant Average
Cable — all types of insulation (Unit = 1000 circuit ft)	Below ground and direct burial			
	0–600 V	0.00388	15.0	24.0
	601–15 000 V — all	0.00617	*95.5	35.0
	In duct or conduit below ground	0.00613	96.8	35.0
Cable (Unit = 1000 circuit ft)	Above 15 000 V	0.00336	16.0	16.0
	601–15 000 V			
	Thermoplastic	0.00387	44.5	10.0
	Thermosetting	0.00889	168.0	26.0
	Paper insulated lead covered	0.00912	48.9	26.8
Cable joints — all types of insulation	Other	0.01832	16.1	28.5
	601–15 000 V			
	In duct or conduit below ground	0.000864	36.1	31.2
Cable joints	601–15 000 V			
	Thermoplastic	0.000754	15.8	8.0
	Paper insulated lead covered	0.001037	31.4	28.0
Cable terminations — all types of insulation	Above ground and aerial			
	0–600 V	0.000127	3.8	4.0
	601–15 000 V — all	0.000879	198.0	11.1
	Aerial cable	0.001848	48.5	11.3
	In trays above ground	0.000333	8.0	9.0
	In duct or conduit below ground			
Cable terminations	601–15 000 V	0.000303	25.0	23.4
	601–15 000 V			
	Thermoplastic	0.004192	10.6	11.5
	Thermosetting	0.000307	451.0	11.3
	Paper insulated lead covered	0.000781	68.8	29.2
Miscellaneous	Inverters	1.254	107.0	185.0
	Rectifiers	0.038	39.0	52.2

*See Tables 48 through 56 in Appendix B for results of a special study on *Effect of Failure Repair Method and Failure Repair Urgency on the Average Hours Downtime per Failure*.

**See Appendix E for data from a later survey.

NOTE: The following tables in Appendix A contain reliability data for equipment categories that had a small sample size (4–7 failures):

Table 6	Circuit breakers used as motor starters
Table 8	Generators driven by motor, diesel, or gas engine
Table 9	Disconnect switches — open
Table 15	Cable joints, 601–15 000 V, above ground and aerial
Table 16	Cable joints, 601–15 000 V, thermosetting
Table 19	Fuses
Table 19	Protective relays

effort is reduced the maintenance costs go down. This may increase the failure rate of the components in the power system and raise the costs associated with failures. There is an optimum amount of maintenance for minimum total owning cost of a complete power system.

The subject of Electrical Preventive Maintenance is discussed in Chapter 5. Some data are shown in Tables 21 and 22 on the effect of the frequency and quality of scheduled electrical preventive maintenance. These data have been used to calculate the effect of maintenance quality on the failure rate of transformers, circuit breakers, and motors shown in Table 23. Unfortunately the data do not relate the amount or cost of component maintenance to the failure rate.

The effect of the cost of component scheduled electrical preventive maintenance on the failure rate has not been included in this book. More industry studies and published data are needed on this subject.

2.5 References²

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3. Summary of Equipment Reliability Data

3.1 Introduction

A knowledge of the reliability of electrical equipment is an important consideration in the design of power distribution systems for industrial plants and commercial buildings. Ideally these reliability data should come from field use of the same type of equipment under similar environmental conditions and similar stress levels. In addition there should be a sufficient number of field failures in order to represent an adequate sample size. It is believed that eight field failures are the minimum number necessary in order to have a reasonable change of determining a failure rate or an "average downtime per failure" to within a factor of two. The types of reliability data needed on each component of electrical equipment are:

- (1) Failure rate—failures per year
- (2) Average downtime to repair or replace a piece of equipment after a failure—hours (or minutes) per failure
- (3) Information on pertinent factors than can have an effect on (1) or (2) above.

These reliability data on each component of electrical equipment can then be used to represent historical experience for use in cost-reliability and cost-availability tradeoff studies in the design of new power distribution systems.

From 1973 to 1975 the Power Systems Reliability Subcommittee of the IEEE Industrial Power Systems Department conducted and published [1], ¹ [2] surveys of electrical equipment reliability in industrial plants. These reliability surveys of electrical equipment and electric utility power supplies were extensive, and summaries of pertinent reliability data are given in this chapter.

(1) Failure rate and outage duration time for electrical equipment and electric utility power supplies

(2) Failure characteristic or failure modes of electrical equipment; that is, the effect of the failure on the system

(3) Causes and types of failures of electrical equipment

¹Numbers in brackets correspond to those in the References at the end of this Section.

(4) Failure repair method and failure repair urgency

(5) Method of service restoration after a failure

(6) Loss of motor load versus time of power outage.

In addition reference is made to summaries of pertinent reliability data and information that are contained in other chapters. This includes:

(7) Maximum length of time an interruption of electrical service will not stop plant production.

(8) Plant restart time after service is restored following a failure that caused a complete plant shutdown.

(9) Cost of power interruptions to industrial plants and commercial buildings.

(10) Example showing that the two power sources in a double-circuit utility supply are not completely independent.

(11) Equipment failure rate multipliers versus maintenance quality.

(12) Percentage of failures caused by inadequate maintenance versus month since maintained

All of the reliability data summarized in the above twelve items are taken from the IEEE surveys of industrial plants [1] [2] and commercial buildings [3]. The detailed reports are given in Appendixes A, B, C, and D. A later survey [4] of the reliability of switchgear bus is included in Appendix E.

3.2 Reliability of Electrical Equipment

The pertinent failure rate and average downtime per failure information for the in-plant electrical equipment are given in Table 11. In compiling these data, a failure was defined as any trouble with a power system component that causes any of the following effects:

(1) Partial or complete plant shutdown, or below-standard plant operation

(2) Unacceptable performance of user's equipment

(3) Operation of the electrical protective relaying or emergency operation of the plant electric system

(4) Deenergization of any electric circuit or equipment

A failure of an in-plant component causes a forced outage of the component, and the component thereby is unable to perform its intended function until it is repaired or replaced.

All of the 60 electrical equipment categories listed in Table 11 have at least 8 or more failures. This is considered an adequate sample size in order to have a reasonable chance of determining a failure rate within a factor of two. Failure rate and average downtime per failure data for an additional seven categories of equipment are contained in [1] (Appendix A.). These additional categories of equipment have between 4 to 7 failures and might be considered by some as too small a sample size, they include:

(1) Circuit breakers used as motor starters

(2) Generators driven by motor, diesel, or gas engine

(3) Disconnect switches—open

(4) Cable joints, 601–15,000 V, above ground and aerial

(5) Cable joints, 601–15,000 V, thermosetting

(6) Fuses

(7) Protective relays

The “failure repair method” and the “failure repair urgency” have a significant effect on the “average downtime per failure” for some equipment categories. Special studies have been

made of this subject for nine equipment categories that are marked with an asterisk (*) in Table 11. These studies are reported in Tables 48 through 56 of [1] (Appendix B).

3.3 Reliability of Electric Utility Power Supplies to Industrial Plants

The "failure rate" and the "average downtime per failure" of electric utility supplies to industrial plants are given in Table 12. Additional details are given in [2] (Appendix D). A total of 87 plants participated in the IEEE survey covering the period from January 1, 1968 through October 1974.

The survey results shown in Table 12 have distinguished between power failures that were terminated by a switching operation versus repair or replacement of equipment. The latter have a much longer outage duration time. Some of the conclusions that can be drawn from these IEEE data are:

(1) The failure rate for single-circuit supplies is about six times that of multiple circuit supplies which operate with all circuit breakers closed; and the average duration time of each outage is about 2.5 times as long

(2) Failure rates for multiple-circuit supplies which operate with either a manual or an automatic throwover scheme are comparable to those for single-circuit supplies, but throwover schemes have a smaller average failure duration than single-circuit supplies

(3) Failure rates are highest for utility supply circuits operated at distribution voltages and lowest for circuits operated at transmission voltages

It is important to note that the data in Table 12 show that the two power sources of a double-circuit utility supply are not completely independent. This is analyzed in an example in 7.1.15, where

for the one case analyzed the actual failure rate of a double-circuit utility supply is more than 200 times larger than the calculated value for two completely independent utility power sources. See Table 36 of Chapter 7 for a summary table comparing the actual and calculated failure rates of a double-circuit utility power supply.

It is believed that utility supply failure rates vary widely in various locations. One of the significant factors in this difference is believed to be different exposures to lightning storms. Thus, average values for the utility supply failure rate may not be valid to use at any one location. Local values should be obtained, if possible, from the utility involved, and these values should be used in reliability and availability studies.

An earlier IEEE reliability survey of electric utility power supplies to industrial plants was published in 1973 and is reported in Table 3 of [1] (Appendix A). The earlier survey had a smaller data base and is not believed to be as accurate nor as up to date as the one summarized in Table 12. The earlier survey of electric utility power supplies had lower failure rates.

3.4 Failure Characteristic of Electrical Equipment

The failure characteristic or failure modes of electrical equipment are important. They identify the effect of the failure on the system and are needed in system reliability studies. Tables 13, 14, and 15 give the failure characteristic of transformers, circuit breakers, and 11 other categories of electrical equipment.

There are some "failure modes" of circuit breakers that require backup protective equipment to operate; for example, "failed to trip" or "failed to inter-

Table 12
IEEE Survey of Reliability of Electric Utility Supplies to Industrial Plants [2]
 (See Tables II, III, IV, V in Appendix D for additional details)

Single Circuit Utility Supplies						
Voltage level	Failures per Unit-Year**			Average Duration (minutes per failure**)		
	λ_S	λ_R	λ	r_S	r_R	r
V ≤ 15 kV	0.905	2.715	3.621	3.5	165	125
15 kV < V ≤ 35 kV	—	1.657	1.657	—	57	57
V > 35 kV	0.527	0.843	1.370	1.5	59	37
All	0.556	1.400	1.956	2.3	110	79

Multiple Circuit Utility Supplies All Voltage Levels						
Switching scheme	Failure per Unit-Year**			Average Duration (minutes per failure**)		
	λ_S	λ_R	λ	r_S	r_R	r
All breakers closed	0.255	0.057	0.312	8.5	130	31
Manual throwover	0.732	*0.118	0.850	8.1	*84	19
Automatic throwover	1.025	0.171	1.196	0.6	96	14
All	0.453	0.085	0.538	5.2	110	22

Multiple Circuit Utility Supplies All Switching Schemes						
Voltage level	Failures per Unit-Year**			Average Duration (minutes per failure**)		
	λ_S	λ_R	λ	r_S	r_R	r
V ≤ 15 kV	0.640	0.148	0.788	4.7	149	32
15 kV < V ≤ 35 kV	0.500	*0.064	0.564	4.0	*115	17
V > 35 kV	0.357	0.067	0.424	6.1	184	34

Multiple Circuit Utility Supplies All Circuit Breakers Closed						
Voltage level	Failures per Unit-Year**			Average Duration (minutes per failure**)		
	λ_S	λ_R	λ	r_S	r_R	r
V ≤ 15 kV	0.175	*0.088	0.263	0.7	*335	112
15 kV < V ≤ 35 kV	0.342	*0.019	0.361	7.0	*120	13
V > 35 kV	0.250	0.061	0.311	11.0	203	49

*Small sample size — less than 8 failures.

**Failure rates λ and average durations r subscripted S and R are, respectively, rates and durations of failures terminated by switching and by repair or replacement. Unsubscripted rates and durations are overall values.

Table 13
Failure Characteristic of Transformers

%	Failure Characteristic
92	Automatic removal by protective equipment
1	Partial failure reducing capacity
7	Manual removal

rupt.” Both of these failure modes would require that a circuit breaker further up the line be opened, and this opening would result in a larger part of the power distribution system being disconnected. Thus the data on failure modes of circuit breakers shown in Table 14 are important in system reliability studies.

The data in Table 15 show that a significant percentage of the failures of

Table 14
Failure Modes of Circuit Breakers
(Percentage of Total Failures in Each Failure Mode)

All Circuit Breakers	Metalclad Drawout			*Fixed Type		Failure Characteristic
	All	601–15 000 V	0–600 V All Sizes	0–600 V All Sizes	All	
%	%	%	%	%	%	
5	5	2	7	8	6	Failed to close when it should
9	12	21	0	0	2	Failed while opening
42	58	49	71	5	4	Opened when it should not
7	6	4	9	5	4	Damaged while successfully opening
2	1	0	0	0	4	Damaged while closing
32	16	24	10	77	73	Failed while in service (not while opening or closing)
1	0	0	0	0	2	Failed during testing or maintenance
1	2	0	3	0	0	Damage discovered during testing or maintenance
1	0	0	0	5	5	Other
100%	100%	100%	100%	100%	100%	Total percentage
165	117	53	59	39	48	Number of failures in total percentage
8	7	0	7	1	1	Number not reported
173	124	53	66	40	49	Total failures

*Includes molded case.

motor starters, motors, and disconnect switches are discovered during testing or maintenance.

3.5 Causes and Types of Failures of Electrical Equipment

Data are given in Tables 16 and 17 on:

- (1) Failures, damaged part
- (2) Failure type
- (3) Suspected failure responsibility
- (4) Failure initiating cause
- (5) Failure contributing cause

The data in Table 17 indicate that inadequate maintenance is suspected as responsible for a significant percentage of the failures for several categories of electrical equipment.

3.6 Equipment Failure Rate Multipliers Versus Maintenance Quality

The relationship between maintenance practice and equipment failure is discussed in 5.3.

Equipment failure rate multipliers versus maintenance quality are given in Table 23 of Chapter 5 for transformers, circuit breakers, and motors. These multipliers were determined in a special study part 6 of [1]; (Appendix B). The failure rate of motors is very sensitive to the quality of maintenance.

The percentage of failures due to inadequate maintenance versus the months since maintained is given in Table 22 of Chapter 5 for circuit breakers, motors, open wire, transformers, and all electrical equipment classes combined. A high percentage of equipment failures are blamed on inadequate maintenance if there has been no maintenance for more than two years prior to the failure.

Table 15
Failure Characteristics of Other Electrical Equipment

Motor Starters	Motors	Gen- erators	Disconnect Switches	Switchgear		Bus — Duct	Open Wire	Cable		Cable Termi- nations	Failure Characteristic
				Bus — Insulated	Bus — Bare			Cable Joints	Cable		
%	%	%	%	%	%	%	%	%	%	%	
37	69	74	72	100	87	90	68	92	96	80	Failed in service
5	1	0	3	0	13	5	2	2	4	2	Failed during testing or maintenance
36	30	0	18	0	0	0	1	2	0	12	Damage discovered during testing or maintenance
20	0	16	6	0	0	5	6	3	0	6	Partial failure
2	0	10	1	0	0	0	23	1	0	0	Other

Table 16
Failure, Damaged Part, and Failure Type

Trans- formers	Circuit Breakers	Motor Starters	Motors	Gen- erators	Dis- connect Switches	Switch- gear		Bus — Insulated	Switch- gear		Bus — Bare	Bus Duct		Open Wire	Cable Joints		Cable Termi- nations		Failure, Damaged Part
						%	%		%	%		%	%		%	%	%	%	
68	0	5	50	7	0	0	0	0	0	15	0	5	0	0	0	0	1. Insulation — winding		
13	2	0	0	0	1	5	8	10	1	0	0	0	0	0	12	0	2. Insulation — bushing		
3	19	10	3	0	14	90	71	65	6	84	91	75	0	0	75	0	3. Insulation — other		
0	1	0	29	2	0	0	0	0	0	0	3	0	0	0	0	0	4. Mechanical — bearings		
0	11	16	3	7	9	0	0	0	0	0	0	0	0	0	0	0	5. Mechanical — other moving parts		
1	6	2	1	4	30	0	0	0	4	1	0	4	0	0	4	0	6. Mechanical — other		
3	6	13	3	10	8	5	0	0	3	1	0	0	0	0	0	0	7. Other electrical — auxiliary device		
1	28	2	0	1	1	0	0	0	3	1	0	0	0	0	0	0	8. Other electrical — protective device		
7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9. Tap changer — no load type		
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10. Tap changer — load type		
3	26	52	11	69	38	0	21	10	84	6	9	10	84	6	9	10	99. Other		
Failure Type																			
58	33	14	28	19	15	65	79	70	34	73	70	55	1.	Flashover or arcing involving ground					
13	10	20	4	3	4	35	21	30	23	1	9	4	2.	All other flash-over or arcing					
12	19	55	32	29	47	0	0	0	25	7	20	37	3.	Other electrical defect					
10	11	11	31	32	14	0	0	0	6	5	0	4	4.	Mechanical defect					
7	27	0	6	16	21	0	0	0	12	14	0	0	99.	Other					

3.7 Failure Repair Method and Failure Repair Urgency

The "failure repair method" and the "failure repair urgency" have a significant effect on the "average downtime per failure." Table 18 shows the percentages of these two parameters for thirteen classes of electrical equipment. A special study on this subject is reported in Tables 48 through 56 of [1] (Appendix B) for nine categories of electrical equipment (marked with an * in Table 11 of this chapter).

The IEEE data on "method of electrical service restoration to plant" are shown in Table 19. A percentage breakdown of the total shows:

Replacement of failed component	
with spare	22%
Repair of failed component	22%
Other	22%
Utility service restored	12%
Secondary selection—manual	11%
Primary selection—manual	7%
Primary selection—automatic	2%
Secondary selection—automatic	2%
Network protector operation-automatic	0 + %

The most common methods of service restoration are replacement of failed component with a spare or repair of failed component. Only 22 percent of the time is primary selection or secondary selection used. This would indicate that most power distribution systems in the IEEE survey were radial.

3.8 Loss of Motor Load Versus Time of Power Outage

A special study has been reported in Table 47 of [1] (Appendix B) on loss of motor load versus time of power outage. For power outages longer than 10 cycle

duration, most plants lose motor load. However, for power outages between 1 and 10 cycle duration, only about half as many plants lose the motor load.

Test results on the effect of fast bus transfers are reported in [5]. This includes 4 kV induction and synchronous motors with the following types of loads: (1) forced draft fan, (2) circulating water pump, (3) boiler feed booster pump, (4) condensate pump, (5) gas recirculation fan. A list of prior papers on the effect of fast bus transfer on motors is also contained in [5].

3.9 Critical Service Loss Duration Time

What is the maximum length of time that an interruption of electrical service will not stop plant production? The median value for all plants is 10.0 seconds. See Table 4 in Chapter 2 for a summary of the IEEE survey of industrial plants.

What is the maximum length of time before an interruption to electrical service is considered critical in commercial buildings? The median value of all commercial buildings is between 5 and 30 minutes. See Table 5 in Chapter 2 for a summary of the IEEE survey of commercial buildings.

3.10 Plant Restart Time

What is the plant restart time after service is restored following a failure that has caused a complete plant shutdown? The median value for all plants is 4.0 hours. See Table 6 in Chapter 2 for a summary of the IEEE survey of industrial plants.

Table 17
Suspected Failure Responsibility, Failure Initiating Cause, and Failure Contributing Cause

Trans- formers	Circuit Breakers	Motor Starters	Motors	Gen- erators	Dis- connect Switches	Switch- gear —		Switch- gear Bare	Bus — Duct	Open Wire	Cable		Cable Termi- nations	Suspected Failure Responsibility	
						%	%				%	%		%	%
39	23	18	15	19	29	5	9	26	0	16	0	0	0	1. Manufacturer— defective com- ponent	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2. Transportation to site — defec- tive handling	0
2	4	51	9	0	6	45	4	16	2	8	0	18	3. Application en- gineering — improper ap- plication	18	0
3	3	0	1	3	4	10	17	5	9	14	50	39	4. Inadequate in- stallation and testing prior to start-up	39	0
11	23	8	17	19	13	35	22	16	30	10	18	22	5. Inadequate maintenance	22	0
9	6	3	4	3	40	0	0	0	2	3	0	0	6. Inadequate op- erating pro- cedures	0	0
2	5	0	0	0	1	0	22	5	5	4	5	0	7. Outside agency — personnel	0	0
4	1	0	1	6	0	0	17	0	21	6	2	8	8. Outside agency — other	8	0
30	36	19	53	48	8	5	9	32	31	38	25	14	9. Other	14	0
Failure Initiating Cause															
23	13	1	6	10	4	5	5	0	26	26	11	12	1. Transient over- voltage distur- bances (light- ning, switching surges, arcing ground fault in ungrounded system)	12	0

Table 17 (Continued)

Trans- formers	Circuit Breakers	Motor Starters	Motors	Gen- erators	Dis- connect Switches	Switch- gear —		Bus Duct	Open Wire	Cable Joints		Cable Termi- nations		Failure Initiating Cause
						gear Insulated	gear Bare			%	%	%	%	
	%	%	%	%	%	%	%	%	%	%	%	%	%	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2. Overvoltage
11	3	1	26	3	4	0	5	30	21	1	0	2	2	3. Overheating
18	18	8	30	3	5	50	18	20	8	29	40	51	51	4. Other insulation breakdown
17	13	8	4	29	17	10	23	45	7	24	31	24	24	21. Mechanical breaking, crack- ing, loosening, abrading or de- forming of static or structural parts
0	5	6	20	3	2	0	0	0	0	0	0	0	0	22. Mechanical burn- out, friction, or seizing of mov- ing parts
1	1	0	3	3	20	0	0	0	10	7	0	4	4	23. Mechanically caused damage from foreign source (digging, vehicular, ac- cident, etc)
1	2	5	0	0	0	0	23	5	14	2	0	2	2	41. Shorting by tools or metal objects
2	1	1	0	0	0	0	9	0	3	0	0	2	2	42. Shorting by birds, snakes, rodents, etc
0	1	0	0	3	0	0	0	0	0	0	0	0	0	51. Loss of con- trol power
1	11	64	5	0	0	0	0	0	0	0	0	0	0	52. Malfunction of protective relay control device, or auxiliary device
0	0	0	0	0	3	0	0	0	0	0	0	0	0	61. Low voltage
0	0	0	0	0	0	0	0	0	0	0	0	0	0	62. Low frequency
25	33	7	5	45	45	35	18	0	11	10	18	4	4	99. Other

Table 17 (Continued)

Trans- formers	Circuit Breakers	Motor Starters	Motors	Gen- erators	Dis- connect Switches	Switch- gear —		Bus — Bare	Bus Duct		Open Wire	Cable Joints		Cable Termi- nations		Failure Contributing Cause
						%	%		%	%		%	%			
13	4	0	5	10	8	0	0	0	6	0	2	0	0	0	0	1. Persistent over- loading
0	1	0	1	6	3	5	0	0	0	0	0	2	0	0	0	2. Above-normal temperatures
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3. Below-normal temperature
0	2	0	7	0	0	0	0	10	0	28	14	13	10	10	4.	Exposure to ag- gressive chem- icals or solvents
6	3	0	10	6	4	15	20	17	1	8	22	12	12	12	5.	Exposure to ab- normal moisture or water
0	0	0	0	3	0	0	5	0	3	2	0	0	0	0	6.	Exposure to non-electrical fire or burning
0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	8.	Obstruction of ventilation by foreign objects or material
24	17	40	34	32	5	20	10	50	3	30	29	24	24	24	9.	Normal de- terioration from age
6	1	0	2	3	0	20	5	11	30	15	2	16	16	16	10.	Severe wind, rain, snow, sleet, or other weather condi- tions
0	2	0	0	6	0	0	0	0	1	0	0	0	0	0	11.	Protective re- lay improperly set
0	1	2	15	0	0	0	0	0	0	0	0	0	0	0	12.	Loss or defi- ciency of lubri- cant
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	13.	Loss or defi- ciency of oil or cooling medium
3	10	3	0	0	0	0	15	6	2	3	0	8	8	8	14.	Misoperation or testing error
3	3	1	5	0	26	40	20	0	2	1	0	0	0	0	15.	Exposure to dust or other con- taminants

Table 18
Failure Repair Method and Failure Repair Urgency

Trans- formers	Circuit Breakers	Motor Starters	Motors	Gen- erators	Dis- connect Switches	Switch- gear —		Bus Duct	Open Wire	Cable Joints	Cable Termi- nations	Failure Repair Method	
						gear Insulated	gear Bare					%	%
47	51	33	78	84	30	95	71	65	70	47	87	60	1. Repair of failed component in place or sent out for repair
53	49	67	22	16	70	5	29	35	9	53	13	34	2. Repair by replacement of failed component with spare
0	0	0	0	0	0	0	0	0	21	0	0	6	99. Other
Failure Repair Urgency													
51	73	66	23	48	20	70	58	80	55	66	56	53	1. Requiring round-the-clock all out efforts
45	22	34	74	52	80	25	33	15	26	28	22	31	2. Requiring repair work only during regular workday, perhaps with some overtime
4	5	0	2	0	0	5	8	5	0	6	22	16	3. Requiring repair work on a non-priority basis
0	0	0	0	0	0	0	0	0	19	0	0	0	99. Other

Table 19
Method of Service Restoration

Total	Electric Utility	Power Supplies	Transformers	Circuit Breakers	Motor Starters	Motors	Generators	Disconnect Switches	Switchgear Bus — Insulated	Switchgear Bus — Bare	Bus Duct	Open Wire	Cable Joints	Cable Joints	Cable Terminations	
%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	
7	1	3	6	0	5	20	0	58	25	20	13	14	28	19	1	1. Primary selection — manual
2	8	0	1	0	0	0	0	0	5	0	4	5	8	0	2	2. Primary selection — automatic
11	1	25	6	0	14	33	0	17	10	10	2	20	32	23	3	3. Secondary selection — manual
2	1	3	8	0	0	0	0	0	0	0	1	0	8	4	4	4. Secondary selection — automatic
0+	0	0	0	0	0	0	0	0	5	0	0	0	0	0	5	5. Network protector operation — automatic
22	5	25	11	12	30	20	3	17	20	35	31	42	24	27	6	6. Repair of failed component
22	2	39	38	10	29	14	77	0	10	35	6	2	0	12	7	7. Replacement of failed component with spare
12	81	0	1	0	0	13	0	0	0	0	1	1	0	0	8	8. Utility service restored
22	1	5	29	78	22	0	20	8	25	0	42	16	0	15	9	9. Other
100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	Total percentage
1204	171	75	160	68	318	15	69	12	20	20	103	122	25	26	2	Total number reported

3.11 Cost of Power Interruptions to Industrial Plants and Commercial Buildings

The cost of power interruptions to industrial plants is summarized in Tables 7 and 8 of Chapter 2.

The cost of power interruptions to commercial buildings is summarized in Tables 9 and 10 of Chapter 2. The effect of computer outages on the costs is shown in these tables.

3.12 Reliability Improvement of Electrical Equipment in Industrial Plants Between 1962 and 1973

The failure rates of electrical equipment in industrial plants have improved considerably during the eleven-year interval between the 1962 AIEE reliability survey [6] and the 1973 IEEE reliability survey [1]. Table 20 shows how much the failure rates have improved for several equipment categories. These data are calculated from a 1974 report [7]. In 1962 circuit breakers had failure rates that were 2.5 to 6.0 times higher than in 1973. The largest improvements in equipment failure rates have occurred on generators, cables, motors, and circuit breakers. The authors discussed some of the reasons for the failure rate improvements during the eleven-year interval. It would appear that manufacturers, application engineering, installation engineering, and maintenance personnel have all contributed to the overall reliability improvement.

The authors also make a comparison the "actual downtime per failure" for all equipment categories shown in the table. In general, the "actual downtime per failure" was larger in 1973 than in 1962.

Table 20
Failure Rate Improvement Factor of Electrical Equipment in Industrial Plants During 11 Year Interval Between 1962 AIEE Survey and 1973 IEEE Survey

Equipment Category	Failure Rate Ratio	
	AIEE (1962)	IEEE (1973)
Generators		
Steam turbine driven		16.0
Gas turbine driven**		13.0
Cable		
Nonleaded in underground conduit		9.7
Nonleaded, aerial		5.8
Lead covered in underground conduit		3.4
Nonleaded in above-ground conduit		1.6
Cable joints and terminations		
Non-leaded		5.3
Leaded		2.0
Motors, 50 hp and larger***		
Synchronous		8.4
Induction		7.1
Circuit breakers		
Metalclad drawout, 0-600 V		6.0
Metalclad drawout, Above 600 V		2.9
Fixed 2.4-15 kV		2.5
Disconnect switches		
Open, above 600 V		3.4
Enclosed, above 600 V		1.6
Open wire		3.4
Transformers		
Below 15 kV, 0-500 kVA****		2.0
Below 15 kV, above 500 kVA		2.0
Above 15 kV		1.6
Motor starters, contactor type		
0-600 V		1.3
Above 600 V		1.3

*Unit = 1000 circuit ft.

**Middle East pipeline data only for 1962.

***250 hp and larger for 1962.

****300-750 kVA for 1973.

3.13 Other Sources of Reliability Data

The reliability data from industrial plants which are summarized in this chapter are based upon References [1] [2] and [3] which were published during 1973-1975. Reference [6] is an earlier reliability survey of industrial plants which had been published in 1962.

Many sources of reliability data on similar types of electrical equipment exist in the electric utility industry. The Edison Electric Institute (EEI) has collected and published reliability data on power transformers, power circuit breakers, metal-clad switchgear, motors, excitation systems, generators, and prime mover generation equipment [8]–[14]. Most EEI reliability activities do not collect outage duration time data; only Reference [4] on prime mover generation equipment contains such data.

Failure rate data and outage duration time data of power transformers, power circuit breakers and buses are given in References [5] and [6]. These data have come from electric utility power systems.

Very little published data are available on the failure modes of power circuit breakers and on the probability of a circuit breaker not operating when called upon to do so. An extensive worldwide reliability survey of the major failure modes of power circuit breakers above 63 kV on utility power systems has been made by CIGRE 13-06 Working Group [7]. Failure rate data and failure per operation data have been determined for each of the major failure modes. Outage duration time data have also been collected. In addition data have been collected on the costs of scheduled preventive maintenance; this includes the manhours per

circuit breaker per year and the cost of spare parts consumed per circuit breaker per year.

ANSI/IEEE Std 500 1977 [17], is a reliability data manual for use in the design of nuclear power generating stations. The equipment failure rates cover such equipment as annunciator modules, batteries and chargers, blowers, circuit breakers, switches, relays, motors and generators, heaters, transformers, valve operators and actuators, instruments, controls, sensors, cables, raceways, cable joints, and terminations. No information is included on equipment outage duration times. Future revisions to ANSI/IEEE Std 500-1977 will include mechanical component data.

The Edison Electric Institute also sponsors the Nuclear Plant Reliability Data System (NRPDS) which collects failure data on electrical components in the safety systems of nuclear power plants. Outage duration time data are collected on each failure. It is expected that NRPDS will become a source of reliability data for future revisions to ANSI/IEEE Std 500-1977.

3.14 References²

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- [2] IEEE COMMITTEE REPORT, Reliability of Electric Utility Supplies to Industrial Plants, IEEE-ICPS Technical Conference, Toronto, Canada, May 5-8, 1975, pp 131-133 in 75-CHO947-1-1A.

² References [2] and [3] are reprinted in Appendixes A, B, C, and D.

- [3] IEEE COMMITTEE REPORT, Cost of Electrical Interruptions in Commercial Buildings, IEEE-ICPS Technical Conference, Toronto, Canada, May 5-8, 1975, pp 124-129 in 75-CHO947-1-1A.
- [4] See Appendix E-IEEE COMMITTEE REPORT, Report of Switchgear Bus Reliability Survey of Industrial Plants, *IEEE Transactions on Industry Applications*, Mar/Apr 1979, pp 141-147).
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- [16] MALLARD, S. A. and THOMAS, V. C. *A Method for Calculating Transmission System Reliability*, Vol PAS-87, Mar 1968.
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4. Evaluating and Improving Reliability of an Existing Plant

4.1 Introduction

The 1974 survey of electrical equipment reliability in Industrial Plants [1]¹ and subsequent investigations showed the utility supply as being the largest single component affecting the reliability of an industrial plant. (See Table 3 in Appendix A and Table 12 in Chapter 3.) The industrial user may or may not be in a position to improve the utility supply reliability and, as a result, must also focus his attention on critical areas within his own plant. A logical approach to the analysis of options available in the industrial plant (in terms of both utility supply and plant distribution) will lead to the most reliability improvement for the least cost. In many instances, reliability improvements can be obtained without any cost by making the proper inquiries.

Most industrial users simply "hook up" to the utility system and do not fully recognize that their requirements can have an impact on how the utility supplies them. A utility is somewhat bound by the system available at the plant site and the investment that can

be made per revenue dollar. However, most utilities are willing to discuss the various supply systems that are available to their customers. Many times, an option is available (sometimes with financial sharing between the user and the utility) that will meet the exact reliability needs of an industrial plant.

A thorough and properly integrated investigation of the entire electric system (plant and supply) will pinpoint the components or sub systems having unacceptable reliability. Some important general inquiries are listed below. Many of these questions apply to both the utility and the plant distribution systems.

- (1) How is the system supposed to operate?
- (2) What is the physical condition of the electrical system?
- (3) What will happen if faults occur at different points?

¹Numbers in brackets correspond to those in the References at the end of this Section.