ACCOMPLISHMENT OF DETAILED ECONOMIC ANALYSIS FOR EVALUATION OF POWER SYSTEM WITH VARYING DEGREES OF RELIABILITY

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DECLARATION BY THE GUIDE

This is to certify that the Mr. ***KASIVISWANADH PANDRANKI***, a student of MBA in Power Management, SAP ID: ***500063273*** of UPES has successfully completed this dissertation report on "A***ccomplishment of detailed economic analysis for evaluation of power system with varying degrees of reliability***" under my supervision.

Further, I certify that the work is based on the investigation made, data collected and analysed by him and it has not been submitted in any other University or Institution for award of any degree. In my opinion it is fully adequate, in scope and utility, as a dissertation towards partial fulfilment for the award of degree of MBA.

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chapter 1

Introduction

1.1. Overview

The objective of this recommended practice is to present the fundamentals of reliability analysis applied to the planning and design of industrial and commercial electric power systems. The design of economic and reliable industrial and commercial power systems is important because of the high cost associated with power outages. It is necessary to consider the cost of power outages when making design decisions for new and existing power systems as well as to have the ability to make quantitative "cost-versus-reliability" trade-off studies.

Economic analysis is a measure to help better allocation of resources that can lead to enhanced income for investment or consumption purposes. Therefore, it is best undertaken at the early stages of the project cycle to enable decision makers to make an informed decision on whether to undertake an investment given various alternatives and their corresponding costs.

The tools of economic analysis can help to answer various questions about the project's overall effect on society, on various stakeholders/beneficiaries, its fiscal aspects and about the project's risks and sustainability.

While each sector has a different set of problems that needs to be addressed, the basic principles of economic analysis can still be applied. The analytical approach and data requirements would have to be adapted or tailored to the specific project. The key here is to select the appropriate level of analysis to inform project decision making.

This document emphasises more on detailed analysis of quantitative cost vs reliability trade-off studies during the design of industrial and commercial power systems.

1.2. Background

Research Background, the modern human society is highly dependent on the reliable operations of critical infrastructures including electrical power systems, drinking water distribution systems, sewage and drainage systems, natural gas transmission and distribution systems, and so forth. These complex systems serve as fundamental infrastructures to support our daily lives. Failures or malfunctions of these systems could cause severe problems such as economic loss, public health crisis or even big panic, riots and human deaths.

In case of electrical power systems (Generation, transmission and distribution) there is considerable gap between the project feasibility analysis to completion of the project in terms of time, cost estimations, rate of returns and inaccurate predictions of the system. It is essential to bridge the gap at the early stages of the project initiation to enable decision makers to take right decisions in allocation of resources and adequate feasibility study.

1.3. Purpose of the study

The objective of conducting a project economic analysis is to assess the sustainability of investment in projects and to inform the design and select projects that can contribute to a sustainable improvement in the welfare of project beneficiaries and the country as a whole.

1.4. Research Hypotheses

Cost analysis includes making a disciplined evaluation of alternate power system design choices.

The decisions can be based upon total owning cost over the useful life of the equipment rather than simply the first cost of the system.

The samples will be taken from O&M (Operation & Maintenance) departments of various plants. The statistical tool used for analysis in the study is Graph and percentage analysis.

chapter 2

Review of literature

- Panida Jirutitijaroen, Prepared Some Optimization Problems in Power System Reliability Analysis, submitted to the Office of Graduate Studies of Texas A&M University, Address two optimization problems involving power system reliability analysis, namely multi-area power system adequacy planning and transformer maintenance optimization.

- Hamza Abunima, Jiashen Teh, Ching-Ming Lai and Hussein Jumma Jabir published A Systematic Review of Reliability Studies on Composite Power Systems: A Coherent Taxonomy Motivations, Open Challenges, Recommendations and New Research Directions: Deals with Providing the critical and systematic studies, findings of reliability of power system.

- Bollen, M.H.J, Literature search for reliability data of components in electric distribution networks: This report gives the result of a literature search for component lifetimes for use in reliability studies of distribution networks.

- IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems: presented the fundamentals of reliability analysis applied to the planning and design of industrial and commercial electric power distribution systems.

chapter 3

Reliability analysis

3.1. Definitions

Some commonly used terms in system reliability analyses are defined here; these terms are also used in the wider context of system reliability activities.

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

- **Component:** A piece of electrical or mechanical equipment viewed as an entity for reliability valuation.

- **Failure (f):** The termination of the ability of a component or system to perform a required function.

- **Failure rate (λ):** The mean (arithmetic average) of the number of failures of a component or system per unit exposure time. The most common unit in reliability analyses is hours (h) or years (y). Therefore, the failure rate is expressed in failures per hour (f/h) or failures per year (f/y).

  Syn: forced outage rate.

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

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

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

- **Mean time between failures (MTBF):** The mean exposure time between consecutive failures of a component.
- **Mean time between maintenance (MTBM):** The average time between all maintenance events, scheduled and unscheduled and includes any associated logistics time.
- **Mean time to failure (MTTF):** The mean exposure time between consecutive repairs (or installations) of a component and the next failure of that component. MTTF is commonly found for non-repairable items such as fuses or bulbs.
- **Mean time to maintain (MTTM):** The average time it takes to maintain a component, including logistics time. MTTM is primarily a measure of the preventative maintenance frequency and durations.
- **Mean time to repair (MTTR or simply r):** The mean time to replace or repair a failed component. Logistics time associated with the repair, such as parts acquisitions, crew mobilization, are not included. It can be estimated by dividing the summation of repair times by the number of repairs and therefore it is practically the average repair time.

  The most common unit in reliability analyses is hours (h/f).
- **Operational availability (Ao):** The instantaneous probability that a component or system will be up or down but differs from Ai, Included is downtime for unscheduled (repair due to failures) and scheduled maintenance, including any logistics time.
- **Reliability:** The ability of a component or system to perform required functions under stated conditions for a stated period.

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

- **Repair downtime (Rdt):** The total downtime for unscheduled maintenance (excluding logistics time) for a given Tp (hours).
- **Repair logistics time (Rlt):** The total logistics time for unscheduled maintenance for a given Tp (hours).

- **System:** A group of components connected or associated in a fixed configuration to perform a specified function.
- **Total downtime events (Tde):** The total number of downtime events (including scheduled maintenance and failures) during the Tp (previously referred to as all actions, maintenance, and repair).
- **Total failures (Tf):** The total number failures during the Tp.
- **Total maintenance actions (Tma):** The total number of scheduled maintenance actions during Tp.
- **Total period (Tp):** The calendar time over which data for the item was collected (hours).
- **Year (y):** The unit of time measurement approximately equal to 8765.81277 hours (h). Any rounding of this value will have adverse effects on analyses depending on the magnitude of that rounding; 8766 is used commonly as it is the result of rounding to 365.25 × 24 (which accounts for a leap year every 4th year); 8760, which is 365 × 24, is the most commonly used value in power reliability field. By convention, 8760 will be used throughout this recommended practice.

3.2. Formulae for calculation reference

A summary of the definitions is compiled in Table-3.1. This table is given for quick reference for some of the formulas that are provided with definition, which will be useful in further calculations.

Calculated data	**Formula for calculation**
Ai, inherent availability	Ai = MTBF/(MTBF + MTTR)
Ao, operational availability	Ao = MTBM/(MTBM + MDT)
λ, failure rate (f/h)	λ = Tf / Tp
λ, failure rate (f/y)	λ = Tf / (Tp / 8760)
MDT, mean downtime (h)	MDT = (Rdt + Rlt + Mdt) / Tde
MTBF, mean time between failures (h)	MTBF = Tp / Tf
MTBM, mean time between maintenance (h)	MTBM = Tp / Tde
MTTM, mean time to maintain (h)	MTTM = Mdt / Tma
MTTR, mean time to repair (h)	MTTR = r = Rdt / Tf
R(t), reliability	R(t) = $e^{-\lambda t}$
Downtime hours per year (DHY)	DHY = (1 – Ao) × 8760
λr, downtime hours per year (DHY)	DHY = λr, where λ is the failure rate per year

3.3. Reliability and availability

In the reliability engineering discipline, the terms reliability and availability have specialized technical meanings. In general, reliability refers to system performance over time. And unfortunately, reliability is often shorthand for reliability engineering and its practice, results, etc. Reliability engineering is a design engineering discipline that applies scientific knowledge to assure a product will perform its intended function for the required duration within a given environment. This includes designing in the ability to maintain, test, and support the product throughout its total life cycle. This is accomplished concurrently with other design disciplines by contributing to the selection of the system architecture, materials, processes, and components (both software and hardware) followed by verifying the selections made by thorough analysis and test. Availability generally refers to the quality or state of being immediately ready for use.

3.3.1. General concepts

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

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

3.3.2. Definitions

Reliability: If the time "t" over which a system must operate and the underlying distributions of failures for its **constituent** elements are known then the system reliability can be calculated by taking the integral, essentially the area under the curve defined by the probability density function (PDF), from "t" to infinity, as shown in given equation 3.1

$$R(t) = \int_t^{\infty} f(t)dt \quad \text{----------} \quad \text{Eq-3.1}$$

where

R(t) is the reliability of a system from time "t" to infinity.

f(t) is the PDF

Availability

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

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

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

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

Inherent availability(Ai)

In general, availability is immediate readiness for use. For this recommended practice we only consider Ai and calculate the metric for Ai explicitly as shown in equation 3.2

$$Ai = \frac{MTBF}{MTBF+MTTR} \quad \text{----------} \quad \text{Eq-3.2}$$

Where

MTBF is Mean time between failures

MTTR is Mean time to repair

If the system never failed, the MTBF would be infinite and Ai would be 100%. Or if it took no time at all to repair the system, MTTR would be zero and again the availability would be 100%. Figure-3.1 is a graph showing availability as a function of MTBF and MTTR [availability is calculated using Equation (3.2)].

Note that you can achieve the same availability with different values of MTBF and MTTR. With lower MTBF, lower levels of MTTR are needed to achieve the same availability and vice versa.

Inherent availability misinterpretations/limitations

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

A common misunderstanding and misuse of the metric is the interpretation that a mean downtime (MDT) can be extracted from an availability metric. For example, a common proclamation is that a facility that has achieved 5-9's availability can expect an average downtime of approximately 5 min per year. It is mathematically true that the system will be down an average of 5 min per year over the long run, i.e., as $t \rightarrow \infty$.

However, If MTBF is known or calculated a priori, to be 87660 h (10 y), then the expected duration of the outage will be 52 min.

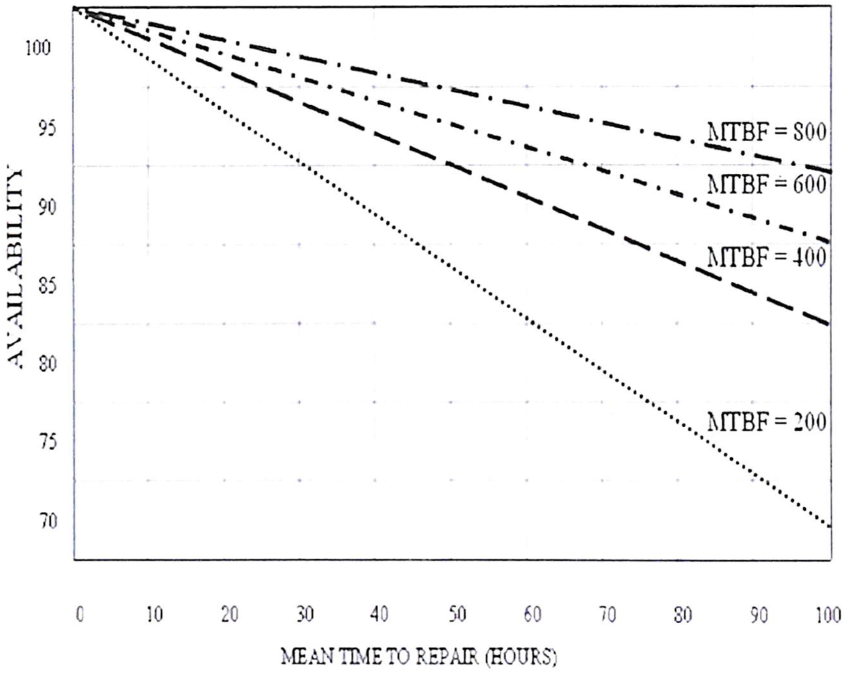


Figure-3.1: Different combinations of MTBF and MTTR yield the same availability

Essentially, an availability metric is a ratio of two parameters. As made clear in Eq-3.2, given an availability metric, there are infinite MTBF and MTTR metrics that can yield the same availability metric. Thus, if availability of a system is estimated through modelling great care must be taken in extracting system MTBF and MTTR metrics.

3.4. Defining frequency and duration of outages and interruptions (λ, MTBF)

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

3.4.1. Frequency of failures, outages

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

3.4.2. Duration of outages and interruptions

Similarly, the duration of outages has historically been described as the MTTR, implying the exponential distribution. In considering descriptive statistics to represent the duration of outages, assumptions, such as the inclusion of scheduled repairs, logistics, spare parts availability, must be explicitly stated.

3.5. Probability distributions

Probability distributions are mathematical equations that describe the probability of a particular event occurring with respect to time. For reliability analysis, what is of great interest is the probability distribution of failure. These functions capture failure characteristics such as wear out failure modes, infant mortality, random, etc. The most common distribution for power reliability analyses is the exponential distribution. This function describes a random failure mode, where the MTBF is the critical parameter.

3.5.1. Probability density functions

Each probability distribution has unique PDFs with the notation f(t). The area under that curve shows the relative probability of a failure occurring before time t (see Figure 3.2). That probability, which becomes the cumulative distribution function (CDF), can be calculated by the integral shown in Equation (3.3):

$$F(t) = \int_0^t f(t)dt \quad \text{-------------------} \quad \text{Eq-3.3}$$

Where,

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

f(t) is the PDF of failure

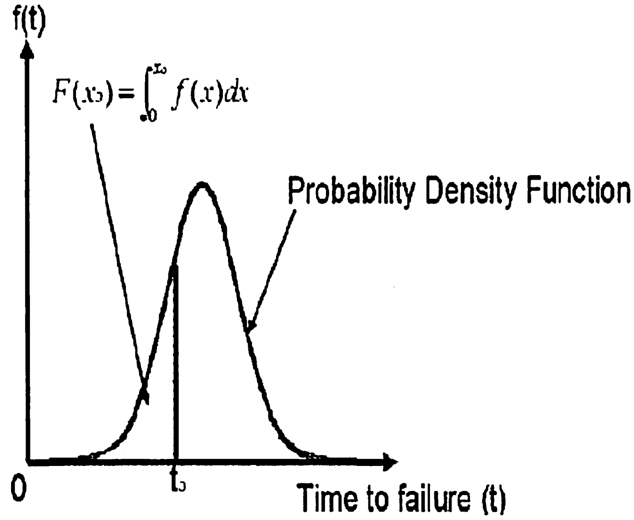


Figure-3.2: Probability of a failure represented by the area under the curve of the PDF

3.5.2. Cumulative distribution function

Plotting F(t) gives us the CDF, which shows the probability of a failure occurring at time t (see Figure 3.3). Finally, the reliability function R(t) is the probability of a component not failing by time t. Therefore R(t) = 1 – F(t).

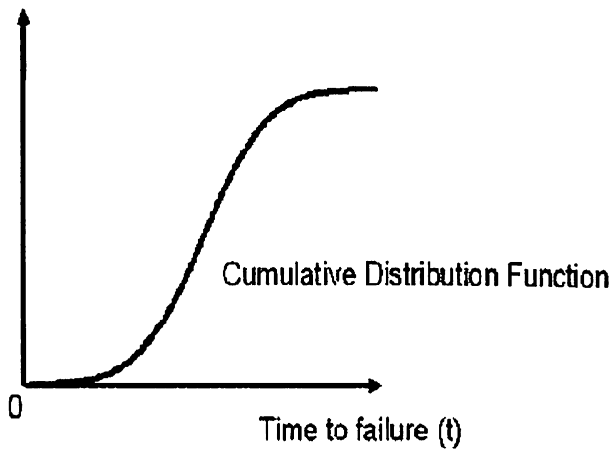


Figure 3.3: The cumulative distribution

3.5.3. Hazard function

The hazard function or hazard rate is the instantaneous failure rate for the remaining population at time t. It is denoted as shown in Equation (3.4):

$$H(t) = \frac{f(t)}{R(t)} \qquad \text{----------} \qquad \text{Eq-3.4}$$

3.5.4. Exponential distribution

The PDF for the exponential distribution is shown in Equation (3.5):

$$f(t) = \lambda e^{-\lambda t} \qquad \text{---------} \qquad \text{Eq-3.5}$$

Thus, the CDF is shown in Equation (3.6):

$$f(t) = 1 - e^{-\lambda t} \qquad \text{---------} \qquad \text{Eq-3.6}$$

And the reliability function is shown in Equation (3.7):

$$R(t) = e^{-\lambda t} \qquad \text{---------} \qquad \text{Eq-3.7}$$

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

The hazard function is as shown in Equation (3.8):

$$H(t) = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda \qquad \text{-----------------} \qquad \text{Eq-3.8}$$

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

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

3.5.5. Weibull distribution

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

3.5.5.1. PDF and CDF

Equation (3.9) shows the Weibull PDF:

$$f(t,\beta,\eta) = \beta/\eta(t/\eta)^{\beta-1}e^{-(\frac{t}{\eta})^{\beta}} \quad \text{---------} \quad \text{Eq-3.9}$$

Where
β is the shape parameter
η is the location parameter

Equation (3.10) shows the Weibull CDF

$$f(t,\beta,\eta) = 1 - e^{-(\frac{t}{\eta})^{\beta}} \quad \text{---------} \quad \text{Eq-3.10}$$

The hazard function for the Weibull distribution is shown in Equation (3.11):

$$H(t,\beta,\eta) = \beta t^{\beta-1} \quad \text{---------} \quad \text{Eq-3.11}$$

When $\beta = 1$, the Weibull distribution is equal to the exponential distribution, as shown in Equation (3.12):

$$F(t, 1, \eta) = 1 - e{-}(t/\eta)1 = 1 - e - (t/\eta) \quad \text{----------} \quad \text{Eq-3.12}$$

Note the variety in PDF shapes depending on the choice of β, as shown in Figure-3.4

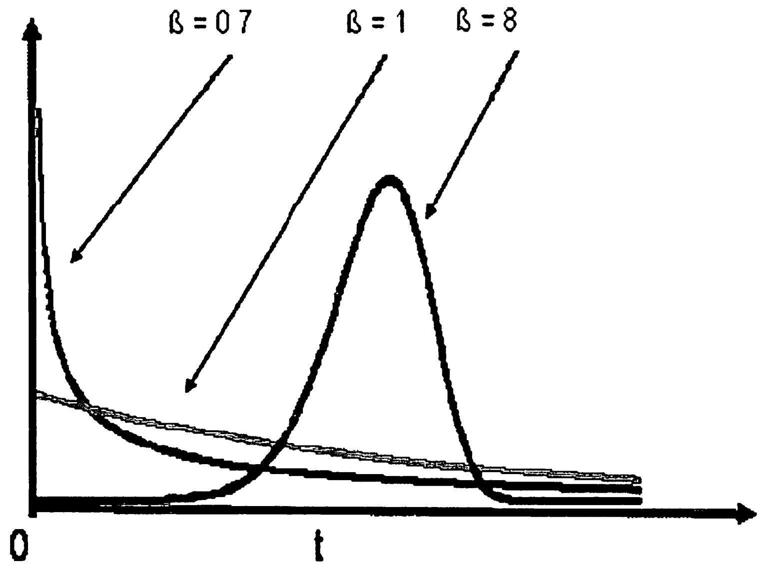


Figure-3.4: Variation of the beta parameter

3.5.6. Calculating reliability for the exponential

If the underlying distribution for each element is exponential and the failure rates, λi, for each element are known, then the reliability of the system can be calculated using Equation (Eq-3.7).

3.5.6.1. Series reliability

Consider the system represented by the reliability block diagram (RBD) in Figure-3.5

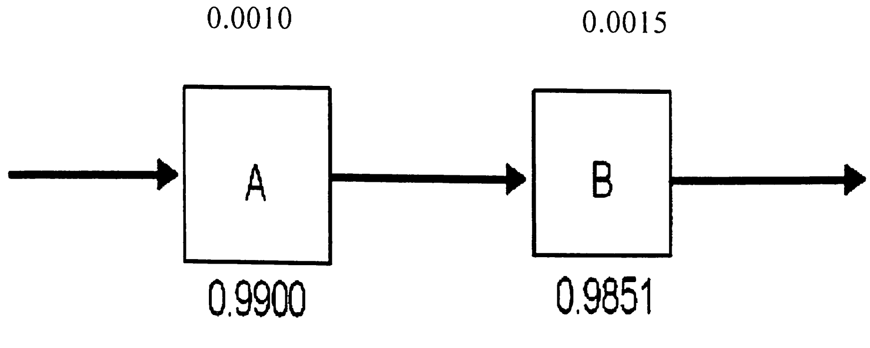


Figure 3.5: Example reliability block diagram

Note: The number above each block in Figure-3.5 is the failure rate λ in failures per million hours. The inverse of the failure rate is the MTTF (exponential failure rate assumed). The number below each block is the reliability calculated using Equation (3.7) with t = 10 million hours.

Series configuration - Weakest link

Components A and B in Figure-3.5 are said to be in series, which means all must operate for the system to operate. Since the system can be no more reliable than the least reliable component this configuration is often referred to as the weakest link configuration. An analogy would be a chain, the strength of the chain is determined by its weakest link.

Series calculation method 1

Since the components are in series, the system reliability can be found by adding together the failure rates of the components. The system failure rate is 0.001000 + 0.001500 = 0.002500. The reliability is shown in Equation (3.13)

$$R(t) = e{-}0.0025\times 10 = 0.9753 \qquad \text{---------} \qquad \text{Eq-3.13}$$

Series calculation method 2

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

3.5.6.2. Reliability with redundancy

Now consider the RBD shown in Figure-3.6

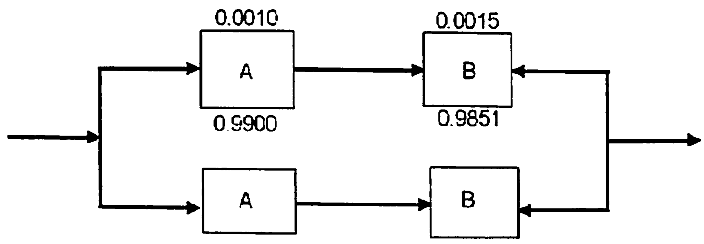


Figure-3.6.: RBD of a system with redundant components

NOTE: The number above each block in Figure-3.6 is the failure rate in failures per million hours. The inverse of the failure rate is the MTTF (exponential failure rate assumed). The number below each block is the reliability.

The system represented by the block diagram in Figure-3.6 has the same components (A and B) used in Figure-3.5, but two of each component are used in a configuration referred to as redundant or parallel. Two paths of operation are possible. The paths are top A-B or bottom A-B. If either of two paths is intact, the system can operate. The reliability of the system is most easily calculated by finding the probability of failure (1–R(t)) for each path, multiplying the probabilities of failure (which gives the probability of both paths failing), and then subtracting the result from 1. The reliability of each path was found in the previous example. Next, the probability of a path failing is found by subtracting its reliability from 1. Thus, the probability of either path failing is 1 – 0.9753 = 0.0247. The probability that both paths will fail is 0.0247 X 0.0247 = 0.0006.

Finally, the reliability of the system is 1 – 0.0006 = 0.9994. A significant improvement over the series configured system, which had a reliability of 0.9753.

3.5.6.3. N + X redundancy

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

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

Case 1: Use 1000 kVA generators, N = 1

Number of generators	Redundancy	Requirement	Availability
1	N	1 of 1	0.99
2	N + 1	1 of 2	0.9999
3	N + 2	1 of 3	0.999999

Case 2: Use 500 kVA generators, N = 2

Number of generators	Redundancy	Requirement	Availability
2	N	2 of 2	0.98
3	N + 1	2 of 3	0.9997
4	N + 2	2 of 4	0.999996

Case 3: Use 250 kVA generators, N = 4

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

3.5.6.4. M of N calculations for reliability

Equation (3.14) can be used for calculating the reliability of an *m* of *n* system for any arbitrary *m* or *n*:

$$R(t) = \sum_{k=m}^{n} \frac{n!}{k!(n-k)!}(e^{-\lambda k})^{k}(1-e^{-\lambda k})^{(n-k)} \qquad \text{---------} \qquad \text{Eq-3.14}$$

where
n is the total number of components
m is the required components

Chapter 4

Planning and design

4.1. Introduction

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

4.2. Fundamentals of power system reliability evaluation

4.2.1. System reliability indexes

The basic system reliability indexes that have proven most useful and meaningful in power generation/distribution system design are as follows:

a. Frequency of generation/load point interruptions
b. Expected duration of generation/load point interruption events

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

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

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

4.2.2. What is an interruption

Evaluation of reliability begins with the establishment of an interruption definition. Such a definition specifies the magnitude of the voltage sag and the minimum duration of such a reduced-voltage period that result in a loss of production or other function for the plant, process, or building in question. Frequently, interruption definitions are given only in terms of a minimum duration and assume that the voltage is zero during that period.

4.2.3. Service interruption definition

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

4.2.4. Data needed for system reliability evaluations

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

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

d) Expected (average) duration of a scheduled outage event

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

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

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

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

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

4.3. Examples of reliability and availability analyses of common low voltage industrial power distribution systems

Seven examples of common low voltage industrial power distribution systems are analysed below:

a) Example 1 - Simple radial
b) Example 2 - Primary selective to 13.8 kV utility supply
c) Example 3 - Primary selective to load side of 13.8 kV circuit breaker
d) Example 4 - Primary selective to primary of transformer
e) Example 5 - Secondary selective
f) Example 6 - Simple radial with a spare transformer
g) Example 7 - Simple radial system with cogeneration

The common low-voltage industrial power distribution systems presented in this document are used only to illustrate the reliability methodologies and are not actual distribution systems.

Only permanent forced outages of the electrical equipment are considered in the seven examples. It is assumed that scheduled maintenance will be performed at times when 480 V power output is not needed. The frequency of scheduled outages and the average duration can be estimated, and if necessary, these can be added to the forced outages given in the seven examples.

When making a reliability study, it is necessary to define what is a failure of the supply to the 480 V point of utilization. Some of the failure definitions that are often used are as follows:

1) Complete loss of incoming power for more than 1 cycle
2) Complete loss of incoming power for more than 10 cycles
3) Complete loss of incoming power for more than 5 s
4) Complete loss of incoming power for more than 2 m

Definition 3) will be used in the seven examples given. This definition of failure can have an effect in determining the necessary speed of automatic transfer equipment that is used in primary-selective or secondary-selective systems. In some cases when making reliability studies, it might be necessary to further define what is a complete loss of incoming power, for example, voltage drops below 70%.

4.3.1. Definition of terminology used in examples

The units that are being used for "failure rate" and "average downtime per failure" are defined as follows:

λ = Failure rate (failures per year)

r = Average downtime per failure (hours per failure) = average time to repair or replace a piece of equipment after a failure. In some cases, this is the time to switch to an alternate circuit when one is available.

4.3.2. Procedure for reliability and availability analysis

The quantitative reliability indexes that are used in the seven examples are the failure rate and the forced hours downtime per year. These are calculated at the 480 V point of use in each example. The failure rate λ is a measure of unreliability. The product λr, (failure rate x average downtime per failure) is equal to the forced hours downtime per year and can be considered a measure of forced unavailability since a scale factor of 8760 converts one quantity into the other. The average downtime per failure r could be called restorability.

The necessary formulas for calculating the reliability indexes are given in below equation. A sample using these formulas is shown in Figure-4.1 for two components numbered "1" and "2" connected in series and Figure-4.2 for two components "3" and "4" connected in parallel. In these samples scheduled outages are assumed to be zero and the units for "λ" and "r" are respectively, failures per year and hours downtime per failure. The equations in Figure-4.1 and Figure-4.2 assume the following:

a) The component failure rate is constant with age.
b) The outage time after a failure has an exponential distribution.
c) Each failure event is independent of any other failure event.
d) The component "up" times are much larger than "down" times: λiri / 8760 < 0.01.

The definitions of the nomenclature used in Figure-4.1 and Figure-4.2 are:

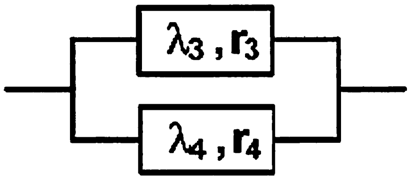
f = Frequency of failures
λi = Failure rate for the ith component expressed in failures per hour
ri = Average hours of downtime per failure for the ith component
s = Series
p = Parallel

$$f_s = \lambda_1 + \lambda_2 \qquad \text{---------} \qquad 4.1$$

$$f_s r_s = \lambda_1 r_1 + \lambda_2 r_2 \qquad \text{---------} \qquad 4.2$$

$$r_s \cong \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_1 + \lambda_2} \qquad \text{----------} \qquad 4.3$$

Figure-4.1- Repairable components in series (both must work for success)



$$f_p = \frac{\lambda_3 \lambda_4 (r_3 + r_4)}{8760} \qquad \text{--------} \qquad 4.4$$

$$f_p r_p = \frac{\lambda_3 r_3 \lambda_4 r_4}{8760} \qquad \text{---------} \qquad 4.5$$

$$r_p = \frac{r_3 r_4}{r_3 + r_4} \qquad \text{---------} \qquad 4.6$$

Figure-4.2- Repairable components in parallel (One or both must work for success)

The formulas shown in Figure-4.2 are approximate and should only be used when both (λ3r3 / 8760) and (λ4r4 / 8760) are less than 0.01.

4.3.3. Reliability of electric utility power supplies to industrial plants

The failure rate and average downtime per failure data for the electric utility power supplies are given in Table-4.1. This includes both single-circuit and double-circuit reliability data. The two power sources in a double-circuit utility supply are not completely independent, and the reliability and availability analysis must take this into consideration.

A failure of an in-plant component causes a forced outage of a 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.

Table-4.1: IEEE survey of reliability of electric utility power supplies to industrial plants

Number of circuits (all voltages)	**λ**	**r**	**λr**
Single circuit	1.956	1.32	2.582
Double circuit Loss of both circuits[b]	0.312	0.52	0.1622
Double circuit—Calculated value for loss of source 1 (while source 2 is OK)	1.644	0.15[c]	0.2466
Calculated two utility power sources at 13.8 kV that are assumed to be completely independent	0.00115[d]	0.66[d]	0.00076

[b]Data for double circuits that had all circuit breakers closed.

[c]Manual switchover time of 9 min to source 2.

[d]Calculated using single-circuit utility power supply data and the equations for parallel reliability shown in Figure-4.5.

In addition to the reliability data for electrical equipment presented, there are some "failure modes" of circuit breakers that require backup protective equipment to operate; for example, "failed to trip" or "failed to interrupt." Both failure modes would require that a circuit breaker farther up the line be opened, and this would result in a larger part of the power distribution system being disconnected. Reliability data on the failure modes of circuit breakers are shown in Table-4.2. These data are used for the 480 V circuit breakers in all seven examples discussed later in this sub-clause. It will be assumed that the "flashed over while open" failure mode for circuit breakers and disconnect switches has a failure rate of 0.0.

Table-4.2 - Failure modes of circuit breakers - Percentage of total failures (Tf) in each failure mode

Percentage of Tf (all voltages)	Failure characteristics
9	Backup protective equipment required (failed while opening)
Other circuit breaker failures	
7	Damaged while successfully opening
32	Failed while in service (not while opening or closing)
5	Failed to close when it should
2	Damaged while closing
42	Opened when it should not
1	Failed during testing or maintenance
1	Damage discovered during testing or maintenance
1	Other
100	**Total percentage**

4.3.4. Example 1: Reliability and availability analysis of a simple radial system

Description: A simple radial system is shown in Figure-4.3. Power is received at 13.8 kV from the electric utility. It goes a very short section of cable through the primary metering, protection and control system and then through a 13.8 kV circuit breaker inside the industrial plant. The circuit continues through a 128.44 m cable in underground conduit and a 91.44 m cable is spliced into the 182.88 m cable. The end of the 128.44 m cable is connected to an enclosed disconnect switch. A short piece of cable connects the enclosed disconnect switch to a transformer, which reduces the voltage to 480 V. The circuit continues through a 480 V main circuit breaker, then a 480 V switchgear bus-bar and then to a second 480 V circuit breaker, 91.44 m of cable in aboveground conduit, to the point where the power is used in the industrial plant

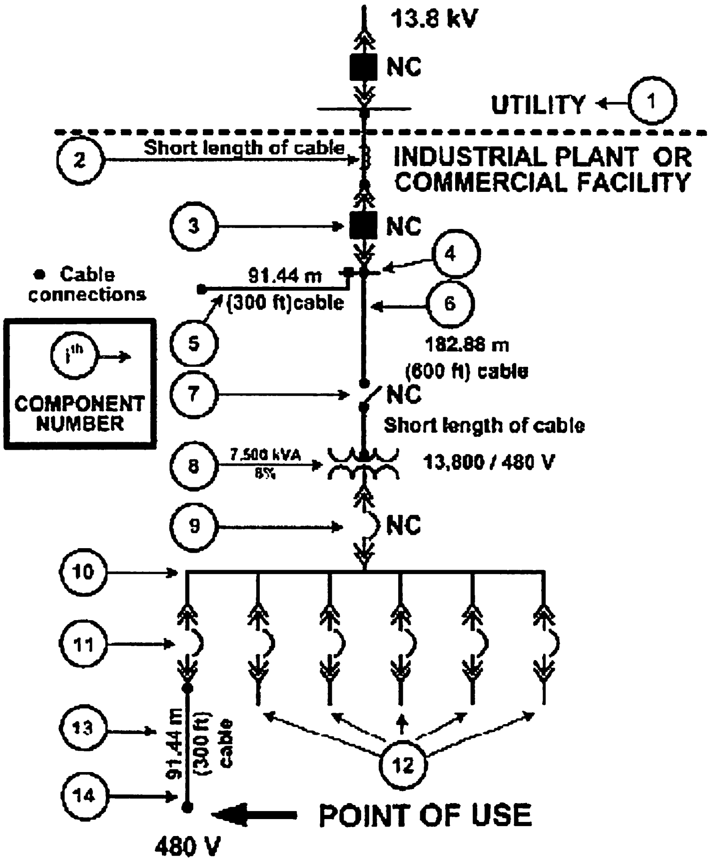


Figure-4.3- Simple radial system (Example-1)

Results: The results from the reliability and availability calculations for the simple radial system shown in Figure-4.3 are given in Table-4.3. The failure rate and the forced hours downtime per year are calculated at the 480 V point of use.

The relative ranking of how each component contributes to the failure rate is of considerable interest is tabulated in Table-4.4.

Table-4.3 - Simple radial system - Failure rate and forced hours downtime per year at 480 V point of use (Example-1)

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.956000	2.582000	0.999705338
2	Primary protection and control system	0.000600	0.003000	0.999999658
3	13.8 kV metal-clad circuit breaker	0.001850	0.000925	0.999999894
4	13.8 kV switchgear bus -insulated	0.004100	0.153053	0.999982529
5	Cable (13.8 kV) 274.32 m (900 ft), conduit playground	0.002124	0.033347	0.999996193
6	Cable terminations (8) at 13.8 kV	0.002960	0.002220	0.999999747
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
8	Transformer	0.010800	1.430244	0.999836757
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus bar	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**1.990940**	**4.279332**	**0.999511730**

The data for hours of downtime per failure are based upon repair failed unit.

Table-4.4 - Simple radial system relative ranking of failure rates

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.956000	2.582000	0.999705338
8	Transformer	0.010800	1.430244	0.999836757
10	480 V switchgear bus bar	0.009490	0.069182	0.999992103
4	13.8 kV switchgear bus - insulated	0.004100	0.153053	0.999982529
6	Cable terminations (8) at 13.8 kV	0.002960	0.002220	0.999999747
5	Cable (13.8 kV), 274.32 m (900 ft), conduit playground	0.002124	0.033347	0.999996193
3	13.8 kV metal-clad circuit breaker	0.001850	0.000925	0.999999894
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
2	Primary protection control system	0.000600	0.003000	0.999999658
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V); 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981

The relative ranking of how each component contributes to the forced hours downtime per year is also of considerable interest is given in Table-4.5.

It might be expected that the power distribution system would be shut down once every 2 years for scheduled maintenance for a period of 24 h. These shutdowns would be in addition to the outage data given in Table-4.3 and Table-4.4.

Table-4.5 - Simple radial system relative ranking of forced hours of downtime per year

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.956000	2.582000	0.999705338
8	Transformer	0.010800	1.430244	0.999836757
4	Switchgear bus -insulated	0.004100	0.153053	0.999982529
10	Switchgear bus bar	0.009490	0.069182	0.999992103
5	Cable (13.8 kV), 274.32 m (900 ft) conduit playground	0.002124	0.033347	0.999996193
2	480 V metal-clad circuit breakers (5) (failed while opening)	0.000956	0.003823	0.999999564
6	Primary protection and control system	0.000600	0.003000	0.999999658
7	Cable connections (8) at 13.8 kV	0.002960	0.002220	0.999999747
12	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
3	13.8 kV metal-clad circuit breaker	0.001850	0.000925	0.999999894
14	Cable connections (2) at 480 V	0.000740	0.000555	0.999999937
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981

Conclusions: The electric utility supply is the largest contributor to both the failure rate and the forced hours downtime per year at the 480 V point of use. It is very important to obtain accurate electric utility supply reliability data to a particular facility. A significant improvement can be made in both the failure rate and the forced hours downtime per year by having two sources of power at 13.8 kV from the electric utility. The improvements that can be obtained are shown in Examples 2, 3, and 4 using a "primary-selective system" and in Example 5 using a "secondary-selective system."

The transformer is the second largest contributor to forced - hours downtime per year. The transformer has a very low failure rate, but the long outage time of 132.43h after a failure results in a large forced hours downtime per year.

The long outage times after a failure for the transformer are all based upon "repair failed unit." These outage times after a failure can be reduced significantly if the "replace with spare" times are used instead of repair failed unit. This is done in Example 6, using a simple radial system with spares.

4.3.5. Example 2: Reliability and availability analysis of primary-selective system to 13.8 kV utility supply

Description: The primary-selective system to 13.8 kV utility supply is shown in Figure-4.4. It is a simple radial system with the addition of a second 13.8 kV power source from the electric utility; the second power source is normally disconnected. If there is a failure in the first 13.8 kV utility power source, then the second 13.8 kV utility power source is switched on to replace the failed power source. Assume that the two utility power sources are synchronized.

The following examples will be analysed:

Example 2a - Assume a 9 min "manual switchover time" to utility power source No. 2 after a failure of source No. 1. The results from the reliability and availability calculations for the primary-selective system to 13.8 kV supply system shown in Figure-4.4. are given in Table-4.6. The data for hours of downtime per failure are based upon repair failed unit.

Example 2b - Assume an "automatic switchover time" of less than 5s after a failure is assumed (loss of 480 V power for less than 5 s is not counted as a failure). The results from the reliability and availability calculations for the primary-selective system to 13.8 kV supply system shown in Figure-4.4 are given in Table-4.7. The data for hours of downtime per failure are based upon repair failed unit.

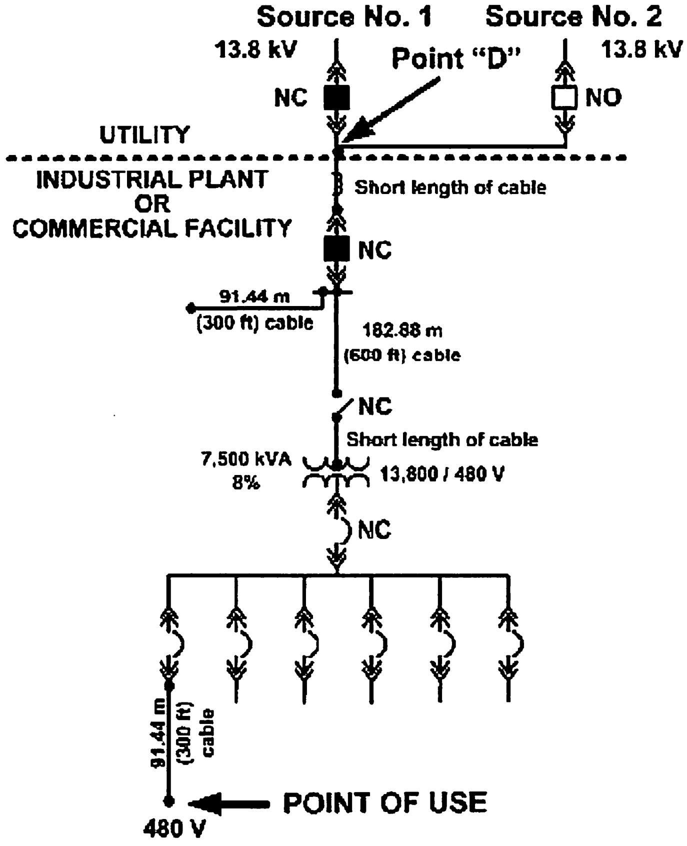


Figure-4.4- Primary-selective system to 13.8 kV utility supply (Example2)

Table-4.6 - Primary-selective system to 13.8 kV utility supply - Failure rate and forced hours downtime per year at 480 V point of use (Ex-2a), assuming a 9-min manual switchover time to utility power source No: 2

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.644000		
2	Primary protection and control system	0.000600		
3	13.8 kV metal-clad circuit breaker	0.001850		
		1.646450	0.246968	0.999971808
	Loss of both 13.8 kV power sources simultaneously	0.312000	0.162240	0.999981480
	Total to point D	1.958450	0.409208	
4	13.8 kV switchgear bus - insulated	0.004100	0.153053	0.999982529
5	Cable (13.8 kV), 274.32 m (900 ft), conduit playground	0.002124	0.033347	0.999996193
6	Cable terminations (8) at 13.8 kV	0.002960	0.002220	0.999999747
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
8	Transformer	0.010800	1.430244	0.999836757
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus bar	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**1.990940**	**2.102614**	**0.999760033**

Table-4.7 - Primary-selective system to 13.8 kV utility supply - Failure rate and forced hours downtime per year at 480 V point of use (Example 2b), assuming a 5s automatic transfer to utility power source No. 2

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.644000		
2	Primary protection and control system	0.000600		
3	13.8 kV metal-clad circuit breaker	0.001850		
		0.0	0.0	1.000000000
	Loss of both 13.8 kV power sources simultaneously	0.312000	0.162240	0.999981480
	Total to point D	**0.312000**	**0.162240**	
4	13.8 kV switchgear bus -insulated	0.004100	0.153053	0.999982529
5	Cable (13.8 kV), 274.32 m (900 ft), conduit playground	0.002124	0.033347	0.999996193
6	Cable terminations (8) at 13.8 kV	0.002960	0.002220	0.999999747
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
8	Transformer	0.010800	1.430244	0.999836757
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus bar	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**0.344490**	**1.855647**	**0.999788213**

Results: Example 2a - If the time to switch to a second utility power source takes 9 min after a failure of the first source, then there would be a power supply outage of 9 min duration. Using the data from Table-4.8 for double-circuit utility supplies, this would occur 1.644 times per year. This in addition to losing both power sources simultaneously 0.312 times per year for an average outage time of 0.52 h. If these utility supply data are added together and substituted into Table-4.3. on the simple radial system, it would result in reducing the forced hours downtime per year at the 480 V point of use from 4.279332 to 2.102614. The failure rate would stay the same at 1.990940 failures per year. These results are given in Table-4.8.

Table-4.8 - Simple radial system and primary-selective system to 13.8 kV utility supply reliability and availability comparison of power at 480 V point of use

Distribution system	λ	λr	**Ai**
Example 1 Simple radial system	1.990940	4.279332	0.999511730
Example 2a Primary-selective system to 13.8 kV utility supply (with 9 min switchover after a supply failure)	1.990940	2.102614	0.999760033
Example 2b Primary-selective system to 13.8 kV utility supply (with switchover in less than 5 s after a supply failure) (see Note)	0.344490	1.855647	0.999788213
NOTE - Loss of 480 V power for less than 5 s is not counted as a failure.			

Example 2b - If the time to switch to a second utility power source takes less than 5s after a failure of the first source, then there would be no failure of the electric utility power supply. The only time a failure of the utility power source would occur is when both sources fail simultaneously. It will be assumed that the data shown in Table-4.8 are applicable for loss of both power supply circuits simultaneously. This is 0.312 failures per year with an average outage time of 0.52 h. If these values of utility supply data are substituted into Table-4.3, it would result in reducing the forced hours downtime per year from 4.279332 to 1.855647h per year at the 480 V point of use. The failure rate would be reduced from 1.990940 to 0.344490 failures per year. These results are also given in Table-4.8.

Conclusions: The use of primary-selective to the 13.8 kV utility supply with 9 min manual switchover time reduces the forced hours downtime per year at the 480 V point of use by about 50%, but the failure rate is the same as for a simple radial system.

The use of automatic transfer equipment that could sense a failure of one 13.8 kV utility supply and switchover to the second supply in less than 5s would give a 6 to 1 improvement in the failure rate at the 480 V point of use (a loss of 480 V power for less than 5s is not counted as a failure).

4.3.6. Example 3: Primary-selective system to load side of 13.8 kV circuit breaker

Description: Figure-4.5 shows a one-line diagram of the power distribution system for primary selective to load side of 13.8 kV circuit breaker. What are the failure rate and the forced hours downtime per year at the 480 V point of use?

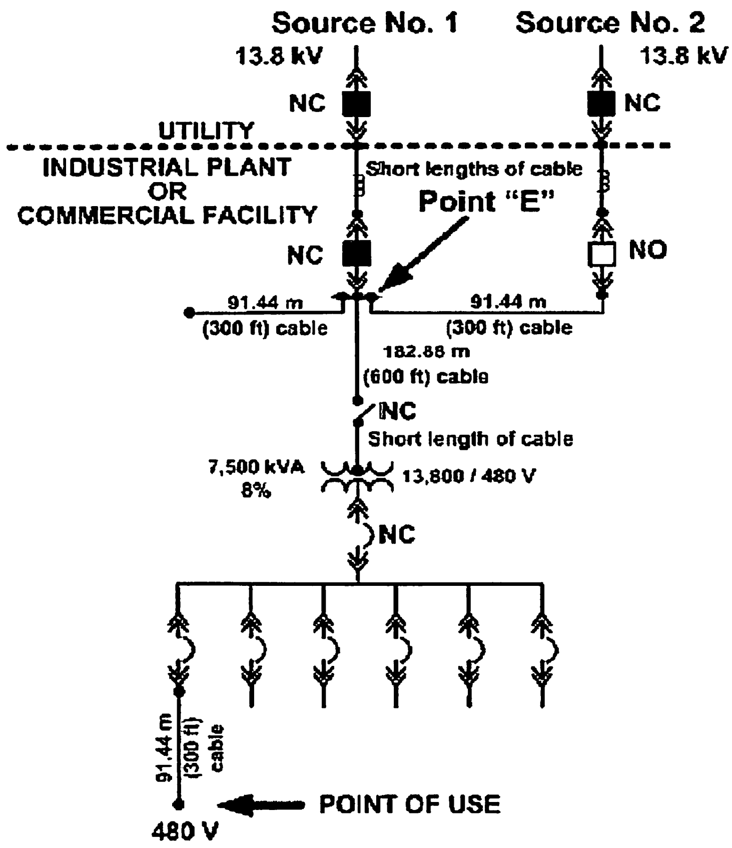


Figure-4.5-Primary-selective system to the load side of 13.8 kV circuit breaker (Example-3)

The following examples will be analysed:

Example 3a - Assume 9 min manual switchover time.

Example 3b - Assume automatic switchover can be accomplished in less than 5s after a failure (loss of 480 V power for less than 5s is not counted as a failure).

Results: The results from the reliability and availability calculations for examples 3a and 3b are given in Table-4.9 and Table-4.10

Table-4.9 - Primary-selective system to load side of 13.8 kV circuit breaker - Failure rate and forced hours downtime per year at 480 V point of use (Example 3a), assuming a 9-min manual switchover time to utility power source No. 2

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.644000		
2	Primary protection and control system	0.000600		
3	13.8 kV metal-clad circuit breaker	0.001850		
	Total through 13.8 kV circuit breaker with 9 min switchover after a failure of source 1 (and source 2 is okay)	1.646450	0.246968	0.999971808
	Loss of both 13.8 kV power sources simultaneously	0.312000	0.162240	0.999981480
4	13.8 kV switchgear bus - insulated	0.004100	0.153053	0.999982529
Total to point E		1.962550	0.562261	
5	Cable (13.8 kV), 365.76 m (1200 ft), conduit belowground	0.002832	0.044462	0.999994924
6	Cable terminations (10) at 13.8 kV	0.003700	0.002775	0.999999683
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
8	Transformer	0.010800	1.430244	0.999836757
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus—bare	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**1.992388**	**2.114285**	**0.999758702**

Table-4.10 - Primary-selective system to load side of 13.8 kV circuit breaker - Failure rate and forced hours downtime per year at 480 V point of use (Example 3b), assuming a 5s automatic transfer to utility power source No. 2

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility			
2	Primary protection and control system			
3	13.8 kV metal-clad circuit breaker			
	Total through 13.8 kV circuit breaker with 9 s switchover after a failure of source 1 (and source 2 is okay)	0.0	0.0	1.000000000
	Loss of both 13.8 kV power sources simultaneously	0.312000	0.162240	0.999981480
4	13.8 kV Switchgear bus-insulated	0.004100	0.153053	0.999982529
Total to point E		0.316100	0.315293	0.999964009
5	Cable (13.8 kV), 365.76 m (1200 ft) conduit playground	0.002832	0.044462	0.999994924
6	Cable terminations (10) at 13.8 kV	0.003700	0.002775	0.999999683
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
8	Transformer	0.010800	1.430244	0.999836757
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus bar	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**0.345938**	**1.867318**	**0.999786881**

Conclusions: The forced hours downtime per year at the 480 V point of use in Example 3 (primary- selective to load side of 13.8 kV circuit breaker) is about the same as in Example 2 (primary-selective to 13.8 kV utility supply). The failure rate is also about the same.

4.3.7. Example 4: Primary-selective system to primary of transformer

Description: Figure-4.6 shows a one-line diagram of the power distribution system for the primary - selective system to primary of transformer. What are the failure rate and the forced hours downtime per year at the 480 V point of use?

The following examples will be analysed:

Example 4a - Assume 9 min manual switchover time.

Example 4b - Assume automatic switchover can be accomplished in less than 5s after a failure (loss of 480 V power for less than 5s is not counted as a failure).

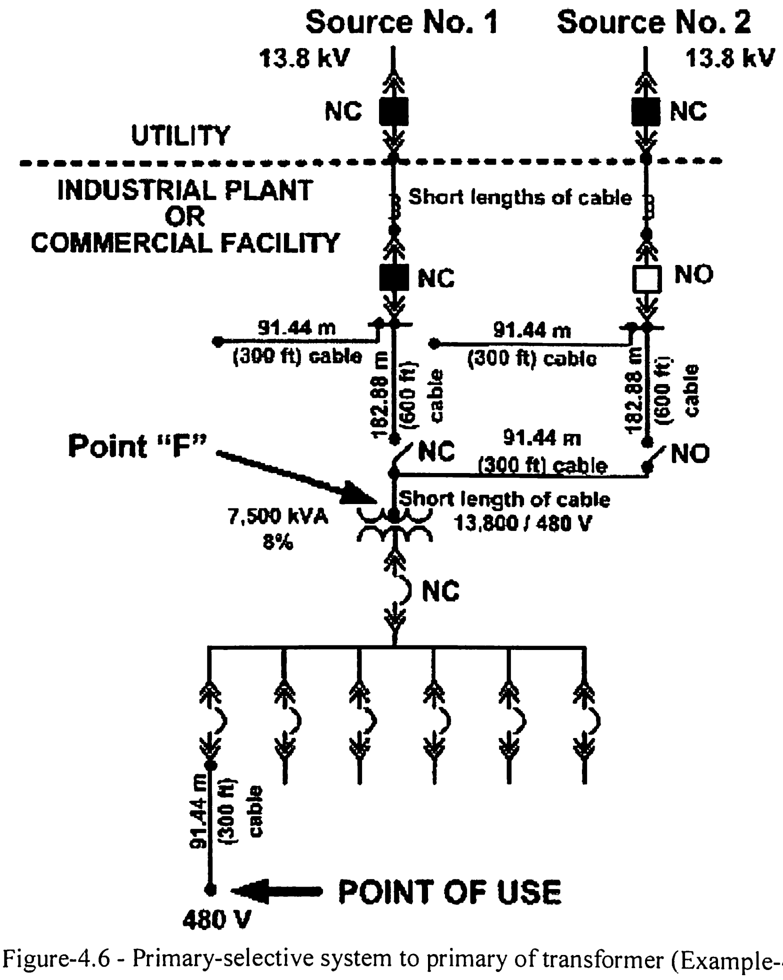


Figure-4.6 - Primary-selective system to primary of transformer (Example-4)

Results: The results from the reliability and availability calculations for examples 4a and 4b are given in Table-4.11 and Table-4.12.

Table-4.11 - Primary-selective system to primary of transformer - Failure rate and forced hours downtime per year at 480 V point of use (Ex - 4a), assuming a 9-min manual switchover time to utility power source No. 2

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.644000		
2	Primary protection and control system	0.000600		
3	13.8 kV metal-clad circuit breaker	0.001850		
4	13.8 kV Switchgear bus - insulated	0.004100	0.153053	0.999982529
5	Cable (13.8 kV), 365.76 m (1200 ft), conduit belowground	0.002832	0.044462	0.999994924
6	Cable terminations (9) at 13.8 kV	0.003330	0.002498	0.999999715
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
	Total through 13.8 kV circuit breaker with 9 min switchover after a failure of source 1 (and source 2 is okay)	1.658452	0.248768	0.999971603
	Loss of both 13.8 kV power sources simultaneously	0.312000	0.162240	0.999981480
	Total to point F	1.970452	0.411008	
8	Transformer	0.010800	1.430244	0.999836757
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus bar	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**1.992018**	**1.914055**	**0.999781548**

Table 4.12 - Primary-selective system to primary of transformer - Failure rate and forced hours downtime per year at 480 V point of use (Example 4b), assuming a 5s automatic transfer to utility power source No. 2

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.644000		
2	Primary protection and control system	0.000600		
3	13.8 kV metal-clad circuit breaker	0.001850		
4	13.8 kV switchgear bus—insulated	0.004100	0.153053	0.999982529
5	Cable (13.8 kV); 365.76 m (1200 ft), conduit belowground	0.002832	0.044462	0.999994924
6	Cable terminations (9) at 13.8 kV	0.003330	0.002498	0.999999715
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
	Total through 13.8 kV circuit breaker with 5 s switchover after a failure of source 1 (and source 2 is okay)	0.0	0.0	1.000000000
	Loss of both 13.8 kV power sources simultaneously	0.312000	0.162240	0.999981480
	Total to point F	0.312000	0.162240	
8	Transformer	0.010800	1.430244	0.999836757
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus bar	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**0.333566**	**1.665287**	**0.999809935**

Conclusions: The forced hours downtime per year at the 480 V point of use in Example 4 (primary- selective system to primary of transformer) is about 55% lower than for the simple radial system shown in Example 1. The failure rate of the simple radial system was about six times larger than the primary-selective system in Example 4b with automatic switchover in less than 5s and approximately the same as Example 4a with a manual switchover time of 9 min.

4.3.8. Example 5: Secondary-selective system

Description: Figure-4.7 shows a one-line diagram of the power distribution system for a secondary- selective system. What are the failure rate and forced hours of downtime per year at the 480 V point of use?

The following examples will be analysed:

Example 5a - Assume a 9-min manual switchover time.

Example 5b - Assume automatic switchover can be accomplished in less than 5s after a failure (loss of 480 V power for less than 5s is not counted as a failure).

Results: The results from the reliability and availability calculations at the 480 V point of use are given in Table-4.13 and Table-4.14.

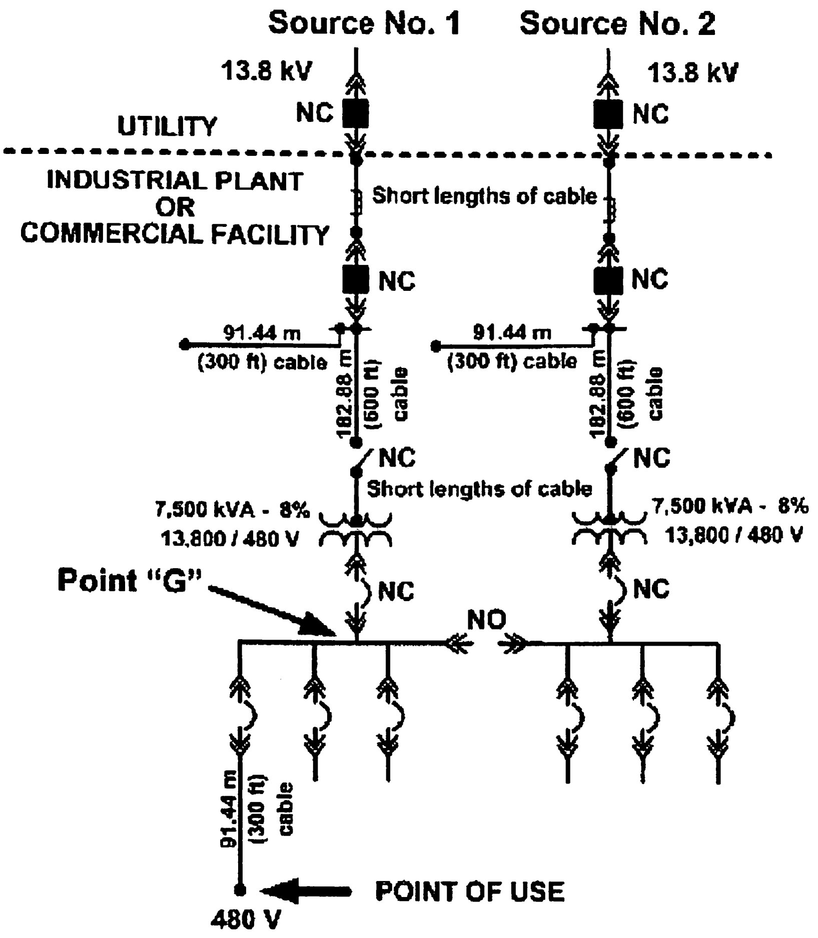


Figure-4.7 - Secondary-selective system (Example-5)

Table-4.13 - Secondary-selective system - Failure rate and forced hours downtime per year at 480 V point of use (Example 5a), assuming a 9-min manual switchover time to utility power source No 2

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.644000		
2	Primary protection and control system	0.000600		
3	13.8 kV metal-clad circuit breaker	0.001850		
4	13.8 kV switchgear bus - insulated	0.004100		
5	Cable (13.8 kV), 365.76 m (1200 ft), conduit playground	0.002124		
6	Cable terminations (9) at 13.8 kV	0.002960		
7	Disconnect switch (enclosed)	0.001740		
8	Transformer	0.010800		
9	480 V metal-clad circuit breaker	0.000210		
Total through 13.8 kV circuit breaker with 9 min switchover after a failure of source 1and source 2 is okay		**1.668384**	**0.250258**	**0.999971433**
	Loss of both 13.8 kV power sources simultaneously	0.312000	0.162240	0.999981480
	Total to point G	**1.980384**	**0.412498**	**0.999952913**
10	480 V switchgear bus—bare	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000038	0.000151	0.999999983
13	Cable (480 V); 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**1.990883**	**0.483814**	**0.999944773**

Table 4.14 - Secondary-selective system—Failure rate and forced hours downtime per year at 480 V point of use (Example 5b), assuming a 5s automatic transfer to utility power source No. 2

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.644000		
2	Primary protection and control system	0.000600		
3	13.8 kV metal-clad circuit breaker	0.001850		
4	13.8 kV switchgear bus - insulated	0.004100		
5	Cable (13.8 kV), 365.76 m (1200 ft), conduit playground	0.002124		
6	Cable terminations (9) at 13.8 kV	0.002960		
7	Disconnect switch (enclosed)	0.001740		
8	Transformer	0.010800		
9	480 V metal-clad circuit breaker	0.000210		
Total through 13.8 kV circuit breaker with 9 min switchover after a failure of source 1 (and source 2 is okay)		**0.00**	**0.0**	**1.000000000**
	Loss of both 13.8 kV power sources simultaneously	0.312000	0.162240	0.999981480
	Total to point G	**0.312000**	**0.162240**	**0.999981480**
10	480 V switchgear bus bar	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000038	0.000151	0.999999983
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**0.322499**	**0.233556**	**0.999973339**

Conclusions: The simple radial system in Example 1 had an average forced hours downtime per year that was about 18 times larger than the secondary-selective system in Example 5b with automatic throw-over in less than 5s. The failure rate of the simple radial system was about six times larger than the secondary-selective system in Example 5b with automatic switchover in less than 5s. These findings clearly demonstrate the impact of automatic transfer systems that do not disrupt the load during the transfer process.

4.3.9. Example 6: Simple radial system with spare

Description: Figure 4.8 shows a one-line diagram of the power distribution system for a simple radial system. What are the failure rate and forced hours of downtime per year of the 480 V point of use if a spare transformer is available and can be installed as a replacement in these average times? The 7500-kVA transformer has the following repair and replacement with spare times 248h repair time vs. 130.0 h to replace with a spare transformer.

The time to replace the transformer data are the actual values obtained from the IEEE Committee Report.

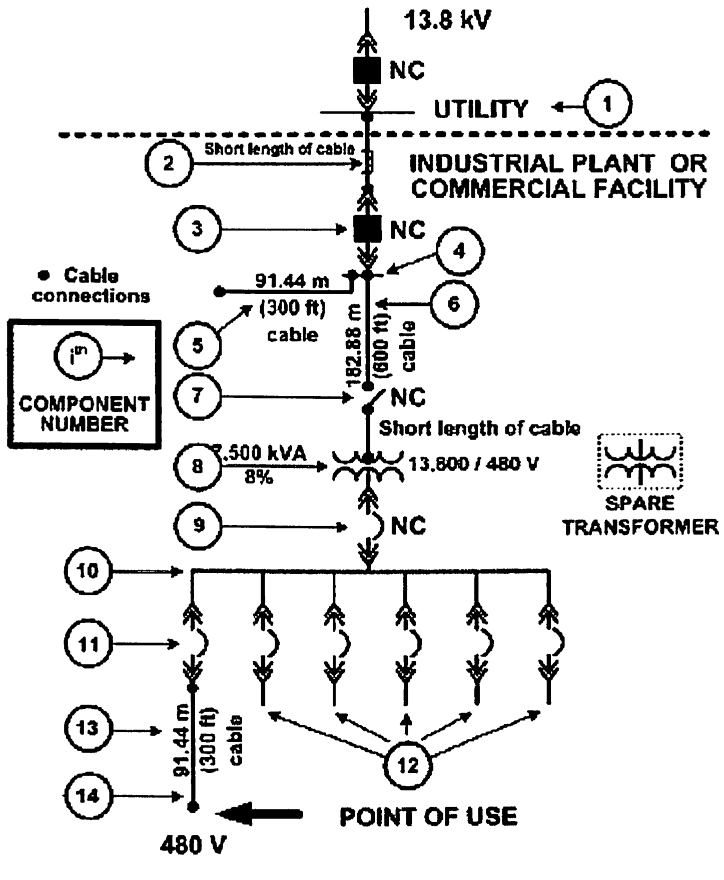


Figure-4.8 - Simple radial system with spare (Example-6)

Results: The results of the reliability and availability calculations are given in Table-4.15. They are compared with those of the simple radial system in Example 1 using average outage times based upon "repair failed unit."

Table-4.15 - Simple radial system with spare transformer - Failure rate and forced hours downtime per year at 480 V point of use (Example 6)

Component number	Component	λ	λr	Ai
1	13.8 kV power source from electric utility	1.956000	2.582000	0.999705338
2	Primary protection and control system	0.000600	0.003000	0.999999658
3	13.8 kV metal-clad circuit breaker	0.001850	0.000925	0.999999894
4	13.8 kV switchgear bus - insulated	0.004100	0.153053	0.999982529
5	Cable (13.8 kV), 274.32 m (900 ft), conduit playground	0.002124	0.033347	0.999996193
6	Cable terminations (8) at 13.8 kV	0.002960	0.002220	0.999999747
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
8	Transformer—replace with spare when it fails—48 h	0.010800	0.518400	0.999940825
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus—bare	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V); 91.44 m (900 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**1.990940**	**3.367488**	**0.999615731**

The data for hours of downtime per failure are based upon replace failed unit.

Conclusions: The simple radial system with spares in Example 6 had a forced hours downtime per year that was 18.3% lower than the simple radial system in Example 1. If the spare replacement time were 48h, then the forced hours of downtime per year would be approximately 21% lower than the simple radial system in Example 1. The failure rate at the 480 V point of use is unchanged.

4.3.10. Example 7: Simple radial system with cogeneration

Description: Figure-4.9 shows a single-line diagram of the power distribution system for a simple radial system with cogeneration. What are the failure rate and forced hours of downtime per year at the 480 V point of use, assuming the utility and cogeneration sources are operated in parallel?

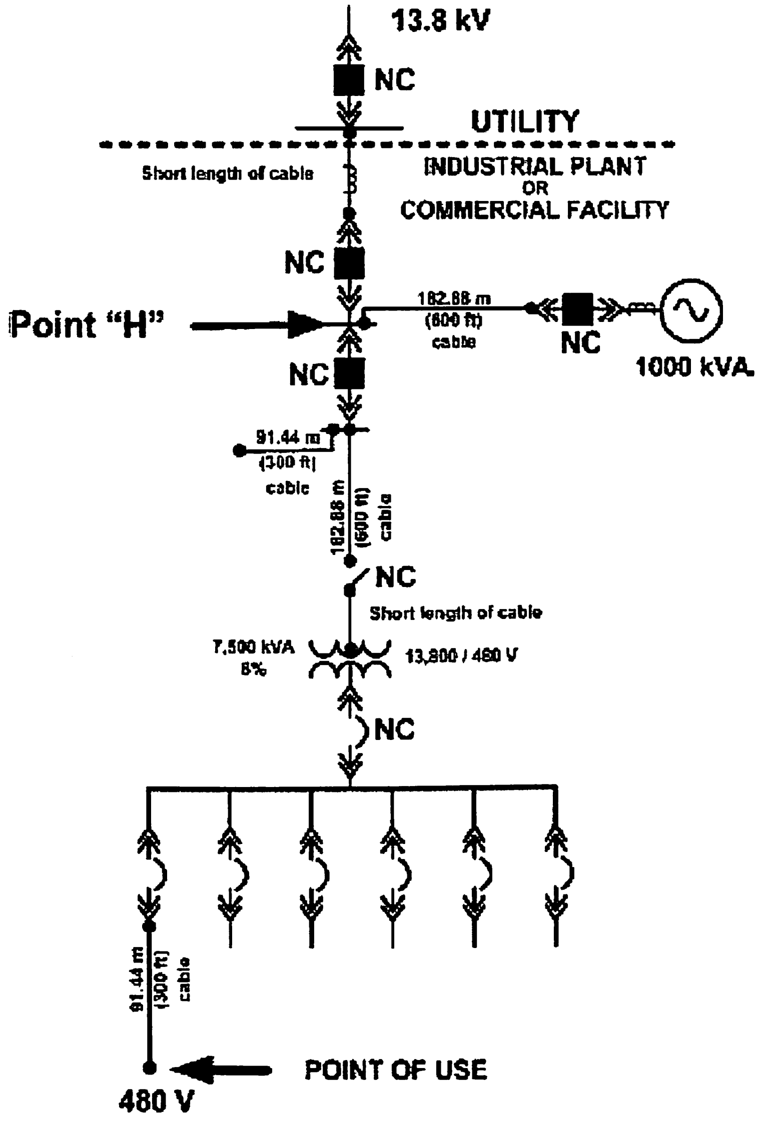


Figure 4.9 - Simple radial system with cogeneration (Example-7)

Results: The results from the reliability and availability calculations are given in Table-4.16.

Table-4.16 - Simple radial system with cogeneration - Failure rate and forced hours downtime per year at 480V point of use (Example 7)

Component number	Component	λ	λr	Ai
1	13.8 kV power source from elec- tric utility	1.644000	2.582000	0.999705338
2	Primary protection and control system	0.000600	0.003000	0.999999658
	Cable connections (2) at 13.8 kV	0.000740	0.000555	0.999999937
3	13.8 kV metal-clad circuit breaker	0.001850	0.000925	0.999999894
	Utility source subtotal	**1.959190**	**2.586480**	**0.999704827**
	Local cogeneration			
	Generator (gas turbine)	1.727600	47.318964	0.994627313
	Control panel generator	0.011110	0.023442	0.999997324
	13.8 kV metal-clad circuit breaker	0.001850	0.000925	0.999999894
	Cable (13.8 kV), 182.88 m (600 ft), conduit playground	0.001416	0.022231	0.999997462
	Cable connections (2) at 13.8 kV	0.000740	0.000555	0.999999937
	Cogeneration subtotal	**1.742716**	**47.366117**	**0.994621988**
	Combined utility and cogeneration sources (assuming independent sources)	0.019470	0.047750	0.999994549
	13.8 kV switchgear bus - insulated	0.004100	0.153053	0.999982529
	Total to point H	**0.023570**	**0.200803**	**0.999977078**
4	13.8 kV metal-clad circuit breaker	0.001850	0.000925	0.999999894
5	Cable (13.8 kV), 274.32 m (900 ft), conduit belowground	0.002124	0.033347	0.999996193
6	Cable connections (6) at 13.8 kV	0.002220	0.001665	0.999999810
7	Disconnect switch (enclosed)	0.001740	0.001740	0.999999801
8	Transformer	0.010800	1.430244	0.999836757
9	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856
10	480 V switchgear bus—bare	0.009490	0.069182	0.999992103
11	480 V metal-clad circuit breaker	0.000210	0.001260	0.999999856

12	480 V metal-clad circuit breakers (5) (failed while opening)	0.000095	0.000378	0.999999957
13	Cable (480 V), 91.44 m (300 ft) conduit aboveground	0.000021	0.000168	0.999999981
14	Cable connections (2) at 480 V	0.000740	0.000555	0.999999937
	Total at 480 V point of use	**0.053069**	**1.741527**	**0.999801235**

Conclusions: The simple radial system in Example 1 yielded an average forced hours downtime per year that was about twice as large as the radial system with cogeneration in Example 7. The largest contributor to the average forced hours of downtime per year is the transformer; for example, if the transformer was replaced with a spare in 48 h, the downtime per year would 0.781933 h compared to 1.741527 h and 0.522733 h compared to 1.741527 for a 24 h spare change out. The failure rate of the simple radial system was about 37 times larger than the radial system with cogeneration in Example 7.

4.3.11. Overall results from seven examples

The results for the seven examples are compared in Table-4.17 that shows the failure rates and the forced hours downtime per year at the 480 V point of use.

These data do not include outages for scheduled maintenance of the electrical equipment. It is assumed that scheduled maintenance will be performed at times when 480 V power output is not needed. This would affect a simple radial system much more than a secondary-selective system because of redundancy of electrical equipment in the latter.

Table-4.17 - Summary - Reliability and availability comparison at 480 V point of use for the seven power distribution system examples

Distribution system	Switchover in less than 5 s		Switchover time 9 min		λ	λr
	λ	λr	λ	λr		
Example-1					1.990940	4.279332
Example-6					1.990940	3.367488
Example-7					0.053069	1.741527
Example-2	0.344490	1.855647	1.990940	2.102614		
Example-3	0.345938	1.867318	1.992388	2.114285		
Example-4	0.333566	1.665287	1.992018	1.914055		
Example-5	0.322499	0.233556	1.990883	0.483814		

4.4. Cost of power outages

4.4.1 Cost of power outages and plant restart time

The forced hours of downtime per year is a measure of forced unavailability and is equal to the product of (failures per year I average hours) downtime per failure. The average downtime per failure could be called restorability and is a very important parameter when the forced hours of downtime per year are determined. The cost of power outages in an industrial plant is usually dependent upon both the failure rate and the restorability of the power system. In addition, the cost of power outages is also dependent on the "plant restart time" after power has been restored. The plant restart time would have to be added to the average downtime per failure when cost vs. reliability and availability studies are made in the design of the power distribution system.

4.4.2 Order of magnitude cost of interruptions

Quantitative reliability assessments permit a cost-benefit analysis for every system reinforcement plan by including customer outage cost into the planning model before the reinforcement plan is implemented. Gauging the cost of customer outages, also known as calculating customer damage functions (CDF) was carried out by surveying customer groups- commercial, industrial and residential, and other company/organization customers by asking them about their experience with outages, including frequency, duration and the cost or inconvenience factor associated with outages. The cost of these outages varied according to customer group and according to the season, time of day and length of outage.

A customer survey was conducted in 2002 by the MidAmerican Energy Company and the cost of interruptions are shown in Table-4.18, Table-4.19 and Table-20 for commercial, industrial and organizational/institutions customers. These interruption costs are presently the most recent published interruption costs available in the technical literature. The cost of interruptions in these tables are defined from various viewpoints, i.e., Table-4.18 represents the average interruption costs per event, Table-4.19 represents the average interruptions costs per annual kWh and Table-4.20 represents the average interruption costs per kW demand. It is important to note that for an organization/institutional customer class the cost of a 2s interruption is greater than a 20min interruption due to the skewed distribution in the survey data that has a significant impact on the average value.

Table 4.18 - Average per event interruption costs

Duration of interruption	Commercial (business) ($)	Industrial ($)	Organization/ institution ($)
2 s	na	na	28,565
1 min	379	14,155	na
20 min	744	20,551	15,373
1 h	1,002	33,436	21,878
4 h	2,299	61,710	53,455
8 h	4,188	92,210	na

Table 4.19 - Average annual per kWh interruption costs

Duration of interruption	Commercial (business) ($)	Industrial ($)	Organization/ institution ($)
2 s	na	na	0.008768
1 min	0.00206	0.00200	na
20 min	0.00705	0.00343	0.004301
1 h	0.00857	0.00642	0.007487
4 h	0.02766	0.01236	0.017766
8 h	0.05146	0.02131	na

Table 4.20 - Average per kW demand costs

Duration of interruption	Commercial (business) ($)	Industrial ($)	Organization/ institution ($)
2 s	na	na	31.54
1 min	9.03	8.98	na
20 min	30.87	13.08	13.48
1 h	37.52	23.41	21.10
4 h	121.15	40.19	53.32
8 h	225.41	67.15	na

4.4.3 Introduction to cost evaluation of reliability

An industrial power distribution system may receive power at 13.8 kV from an electric utility and then distribute the power throughout the plant for use at the various locations. One of the questions often raised during the design of the power distribution system is whether there is a way of making a quantitative comparison of the failure rate and the forced hours downtime per year of a secondary-selective system with a primary-selective system and a simple radial system. This comparison could be used in cost-reliability and cost-availability trade-off decisions in the design of the power distribution system. The estimated cost of power outages at the various plant locations could be factored into the decision as to which type of power distribution system to use. The decisions could be based upon "total owning cost over the useful life of the equipment" rather than "first cost."

4.4.4 Cost data applied to examples of reliability and availability analysis of common low-voltage industrial power distribution systems

4.4.4.1 Cost evaluation of reliability and availability predictions

Cost evaluations were made of the reliability and availability predictions of five power distribution systems; examples will be presented. The revenue requirement (RR) method will be utilized to determine the most cost-effective system.

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".

The essence of the RR method is that for each alternative plan being considered, the minimum revenue requirements (MRR) are determined. This reveals the amount of product needed to be sold to achieve minimum acceptable earnings on the investment involved plus all expenses associated with that investment. These MRR for alternative plans may be compared directly. The plan having the lowest MRR is the economic choice.

MRR are made up of and equal to the summation of the following:

a) Variable operating expenses

b) Minimum acceptable earnings

c) Depreciation

d) Income taxes

e) Fixed operating expenses

These MRR may be separated into two main parts, one proportional and the other not proportional to investment in the alternative. This may be expressed Equation 4.7

$$G = X + CF \quad \text{-----------} \quad 4.7$$

where

G is the MRR to achieve minimum acceptable earnings

X is the nonfixed or variable operating expenses

C is the capital investment

F is the fixed investment charge factor

The last term in Equation 4.7, the product of C and F, includes the items b), c), d), and e) listed in the preceding paragraph. Equation 4.7 is now discussed.

X (variable expenses): The effect of the failure of a component is to cause an increase in variable expenses. The seriousness of the of this increase 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

- Effect repairs, if it is a radial system or 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 of 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 1h, perhaps no labor costs are saved. But, if plant downtime exceeds 8 h, labor costs may be saved.

If it is assumed 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 by Equation 4.8

$$X = \lambda\,[x_i + (g_p - x_p)\,(r + s)] \qquad \text{------------} \qquad 4.8$$

where

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

For example, assume that

- λ is the 0.1 failure per year
- x_i is the $55,000 per failure, extra expenses incurred
- g_p is the $22,000 per hour, revenues lost
- x_p is the $16,000 per hour, expenses saved
- r is the 10 h per failure
- s is the 20 h per failure

Then, variable expenses affected would be

$$X = (0.1)\,[\$55{,}000 + (\$22{,}000 - \$16{,}000)\,(10 + 20)] = \$23{,}500 \text{ per year}$$

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 an expense.

A failure rate of 0.1 failure per year is equivalent to a mean time between failures (MTBF) of 10 years. These results can be expected since this is probability. But in a specific case, there might be two failures in one 10-year period and no failures in another 10-year period. By considering many similar cases, it is expected to have an average of 0.1 failure per year with each failure costing an average of \$235,000. This gives an equal average amount per year in the previous example of \$23,500.

The point is that even though the actual failure cost \$235,000 each and occur once in every 10 years. Given example is just as likely to occur in any of the 10 years. The equivalent amount of \$23,500 per year is the average value of one failure in 10 years.

C (Capital investment): Each power system involves different investments based on type of system. 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 of system. 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 in comparing alternatives, the investment is multiplied by an F factor. This factor is usually the same for alternative plans of the sort being considered here, but this is not necessarily the case.

F (investment charge factor):

The factor F includes the following items that are constant in relation to the investment:

- Minimum acceptable rate of return on investment, allowing for risk
- Income taxes
- Depreciation
- Fixed expenses

Equation (4.9) is used to calculate the F factor:

$$F = \frac{(S_c a_L / f_r) - t d_t}{1 - t} + e \qquad \text{-------------} \quad 4.9$$

This may also take the form shown in Equation (4.10):

$$F = r + d + t + e \qquad \text{--------------} \qquad 4.10$$

where

a_n	is $R + d_n$, amortization factor or leveling factor
d_n	is $R/(S_n - 1)$, sinking fund factor
S_n	is the $(1 + R)^n$, growth factor or future value factor
n	is the period of years, such as c or L
c	is the years prior to start-up that an investment is made
L	is the life of investment years
R	is the minimum acceptable earnings per \$ of C (investment)
f_r	is the probability of success or risk adjustment factor
t	is the income taxes per \$ of C (investment)
d_t	is the income tax depreciation, levelized per \$ of C (investment) = 1/L, d_t = 1L
e	is the fixed expenses per \$ of C (investment)
r	is the levelized return on investment per \$ of C (investment)
d	is the levelized depreciation on investment per \$ of C (investment)
t	is the levelized income taxes on investment per \$ of C (investment)
Sc	is (1 + R)c
S_L	is (1 + R)L
d_L	is R/(SL – 1)
a_L	is R + dL

For example, assume:

L	to be 20 years, life of the investment
c	to be 1 year
R	to be 0.15, minimum acceptable rate of return
fr	to be 1, risk adjustment factor
t	to be 0.5, income tax rate
dt	to be 1/L = 0.05
e	to be 0.0825

Then

Sc	is $(1 + R)^c = (1 + 0.15)1 = 1.15$
S_L	is $(1 + R)^L = (1 + 0.15)20 = 16.37$
d_L	is $R/(S_L - 1) = 0.15/(16.37 - 1) = 0.0.0098$
a_L	is $R + d_L = 0.15 + 0.0098 = 0.1598$

Substituting into Equation *(4.9)* to calculate the F factor, results in F = 0.04

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%, 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, fr, 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 Equation *(4.9)*.

4.4.4.2 Steps for economic comparisons

a) Prepare single-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.

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

c) Determine F, the fixed investment charge factor F from Equation (*4.9*).

d) Calculate G = X + CF, the MRRs G of each plan from Equation (*4.7*).

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

4.4.4.3 Description of cost evaluation problem

Management insists that the engineer utilize an economic evaluation in any capital improvement program. The elements to be included and a method of mathematically equating the cost impact to be expected from electrical interruptions and downtimes against the cost of a new system were presented in this sub-clause. It was pointed out that there are several acceptable ways of accomplishing the detailed economic analysis for evaluation of systems with varying degrees of reliability. One of those considered acceptable, the RR method was presented in detail and this method will be used in the analysis of five examples.

The five example systems included are:

- Example 1 - Simple radial system - Single 13.8 kV utility supply
- Example 2b - Primary selective system to 13.8 kV utility supply (dual) - switchover time less than 5 s
- Example 4 - Primary selective system to primary of transformer - 13.8 kV utility supply (dual) - manual switchover in 9 min
- Example 5b - Secondary-selective system with switchover time less than 5 s
- Example 7 - Simple radial system with cogeneration

Table 4.23 lists the expected failures per year and the average downtime per year for each of the examples. These data will be used to show which of the examples has the MRR making allowances for:

a) Plant start-up time
b) Revenues lost
c) Variable expenses saved
d) Variable expenses incurred
e) Investment
f) Fixed investment charges

One of the benefits of such a rigidly structured analysis is that the presentation is made in a sequential manner utilizing cost/failure data prepared with the assistance of management. With this arrangement, the results of the evaluation are less likely to be questioned than if a less sophisticated method was used.

4.4.4.4 Procedures for cost analyses

Utilizing the single-line diagrams for the five examples, a component quantity take-off of each system was made, and the installed unit costs assigned for each component. In the case of the dual 13.8 kV utility company's supply, the basic cost of the second supply was estimated based on a hypothetical case, assuming that a one-time only cost would be incurred. The extension of the costs results in the overall installed cost for each of the five examples. A summary of the installed costs for each example system is presented in Table-4.21 and Table-4.22. All the unit cost estimates are assumed for illustrative purposes. The utility service standby charge (i.e., a lump cost) assumes that the utility company's alternative primary service distribution system will require upgrading and a reserve capacity will be required in the utility company's substation. A lump sum (LS) of $250,000 is assumed in this analysis. The RR method will be used to calculate the total cost in dollars per year of both the "installed cost" and the "cost of unreliability" for the five examples.

Table-4.21 - Installed costs of example systems 1, 2b, and 4

Item	Unit cost ($)	Example 1 - Simple radial system – single 13.8 kV utility supply		Example 2b Primary-selective system to 13.8 kV utility supply (dual)		Example 4 Primary-selective system to primary of transformer	
		Quantity	Total cost ($)	Quantity	Total cost ($)	Quan- tity	Total cost ($)
Utility service standby charge - LS		—	—	LS	$250,000	LS	250.000
Basic equipment							
Medium-voltage circuit breaker, each	75	1	75	1	75	2	150
Medium-voltage circuit cable, linear feet	35	900	31,500	900	31,500	2100	73,500
1000 kVA, transformer each	100	1	100	1	100		100
1000 kVA Transformer - 3-position switch, each	100					1	
1600 A low-voltage circuit breaker, each	25	1	25	1	25	1	25
600 A MCCB, each	15	6	90	6	90	6	90
Low-voltage cable, linear feet	5	300	1,500	300	1,500	300	1,500
Subtotal - basic equipment cost			33,290		33,290		75,365
Total cost		**33,290**		**283,290**		**325,365**	

NOTE: All installed costs are hypothetical and are solely for the purpose of illustrating the cost analyses methodology.

Table-4.22 - Installed costs of example systems 5b and 7

Item	Unit cost ($)	Example 5b Secondary-selective system		Example 7 Simple radial with cogeneration	
		Quantity	Total cost ($)	Quantity	Total cost ($)
Utility service standby charge - LS		LS	250,000	—	—
LS cogeneration plant					350,000
Basic equipment					
Medium-voltage circuit breaker, each	75	2	150	3	225
Medium-voltage circuit cable, linear feet	35	1800	63,000	1500	52,500
1000 kVA transformer, each	100	2	200	1	100
1000 kVA transformer—3-position switch, each	100				
1600 A low-voltage circuit breaker, each	25	3	75	1	25
600 A MCCB, each	15	6	90	6	90
Low-voltage cable, linear feet	5	300	1,500	300	1,500
Subtotal—Basic equipment cost			65,015		54,440
Total cost		**315,015**		**404,440**	
NOTE—All installed costs are hypothetical and are solely for the purpose of illustrating the cost analyses methodology.					

4.4.4.5 Assumed cost values

The following common cost factors were assumed:

- 10 h/failure - Plant start-up time after a failure, s
- \$22,000/h - Revenues lost per hour of plant downtime, g_p
- \$16,000/h - Variable expenses saved per hour of plant downtime, x_p
- \$55,000/failure- Variable expenses incurred per failure, x_i
- 0.4 per year - Fixed investment charge factor, F

These values are shown in Table-4.23 after (2), (4), (5), (8) and (13) respectively.

Table 4.23 - Sample reliability economics problem of example systems

		Example 1	**Example 2b**	**Example 4**	**Example 5b**	**Example 7**
1	r - Component repair time or transfer time to restore service, whichever is less, hours power failure	2.15	5.39	0.96	0.72	32.82
2	s - Plant start-up time, hours per failure	10.00	10.00	10.00	10.00	10.00
3	r + s	12.15	15.39	10.96	10.72	42.82
4	g_P - Revenues lost per hours of plant down- time, $/h	$22,000	$22,000	$22,000	$22,000	$22,000
5	x_P - Variable expenses saved, $/h	$16,000	$16,000	$16,000	$16,000	$16,000
6	$g_P - x_P$	$6,000	$6,000	$6,000	$6,000	$6,000
7	$(g_P - x_P)(r + s) =$ $/failure	$72,896	$92,320	$65,765	$64,345	$256,897
8	x_i - Variable expenses incurred per failure, $/failure	$55,000	$55,000	$55,000	$55,000	$55,000
9	Item (7) + (8) $/failure	$127,896	$147,320	$120,765	$119,345	$311,897
10	λ - failure rate per year	1.99	0.34	1.99	0.32	0.05
11	Item (9) x (10), X $/year	$254,634	$50,750	$240,566	$38,489	$16,552
12	C - Investment (installed costs)	$13,316	$283,290	$325,365	$315,015	$404,440
13	F - Fixed investment charge factor, per year	0.40	0.40	0.40	0.40	0.40
14	CF=Fixed investment charges, $/year	$13,316	$113,316	$130,146	$126,006	$161,776
15	G = X + CF [Items (11) + (14)], MRR, $/year	$267,950	$164,066	$370,712	$164,495	$178,328
	Economic choice		**Example 2b**			

4.4.4.6 Results and conclusions

The MRR for each of the five examples are shown in item (15) at the bottom of Table-4.23. Some of the conclusions that can be made are tabulated below:

- *Example 1* - Simple radial system - single 13.8 kV utility supply

  This system requires the least initial investment ($33,290). However, its MRR of $267,950 per year is the second highest of the five examples analyzed.

- *Example 2b* - Primary-selective system to 13.8 kV utility supply (dual) with switchover time less than 5s

  This system requires an initial investment of $283,290; however, the MRR is $164,066 per year, which is the least of the five examples.

  Based on the data presented, Example 2b would be selected since it has the lowest MRR.

- *Example 4* - Primary selective system to primary of transformer, 13.8 k V utility supply (dual) - manual switchover time of 9 min

  This system shows next to highest initial cost of $325,365 and the highest MRR of $370,712 per year. A major contributor to the high MRR is the fact that while a dual system has been provided, the utility supplies' 9 min manual switchover requirement increases the failure rate and downtime to account for its high MRR. If an automatic switchover were utilized, the example would be competitive with Example 2b.

- ***Example 5b*** – Secondary selective system, with switchover time less than 5 s

  This system requires the third highest initial investment ($315,015) and produces the second lowest MRR of $164,495 per year.

- *Example 7* - Simple radial system with cogeneration

  This system matches Example 5b (secondary selective system with switchover time less than 5 s) with the highest initial investment of $404,440 and produces the third MRR of $178,328 per year.

Chapter 5

Economic & reliability analysis of 180MW Solar Plant substation

5.1. Overview of 180 MW Solar Plant Substation.

Overall Plant capacity is 180MW. Five blocks (Solar modules/inverters) of each 36MW (intern 6Nos of Inverter Stations of each capacity 6MW) will generate at 0.8kV level at inverter output and then steped up to 33kV level by 0.8/33kV Inveter Duty Transfomrer (IDT). 6Nos 6MVA IDTs are connected in a ring main unit and pooled and connected to a 33kV feeder at 33/220kV Substation. All such five blocks are connected in a similar way and 180MW will be connected to 33kV Bus at 33/220kV Substation. To minimise the transmission line losses and availability of grid at 220kV level near the plant it is required to evacuate the power at 220kV voltage level to grid, we have step up the voltage to 220kV by 33/220kV transformers. With 220kV double circuit transmission line 180MW power is evacuated to the grid.

33kV (From Inverters to 33kV Bus) system and 220kVsystem (From 220kV bus to 220kV Grid) will remain same for all proposals, As generation and evacuation system stays constant in all the cases. Step-up transformers and associated switchgear equipment will change as per the proposals for economic analysis.

Proposal - 1: In this proposal we have considered 3 number of 33/220kV transformers and associated switchgear equipment (shown in Fig-5.1 Single line diagram of 180MW substation proposal-1). Keeping the costs of 33kV (From Inverters to 33kV Bus) system and 220kV system (From 220kV bus to 220kV Grid) constant.

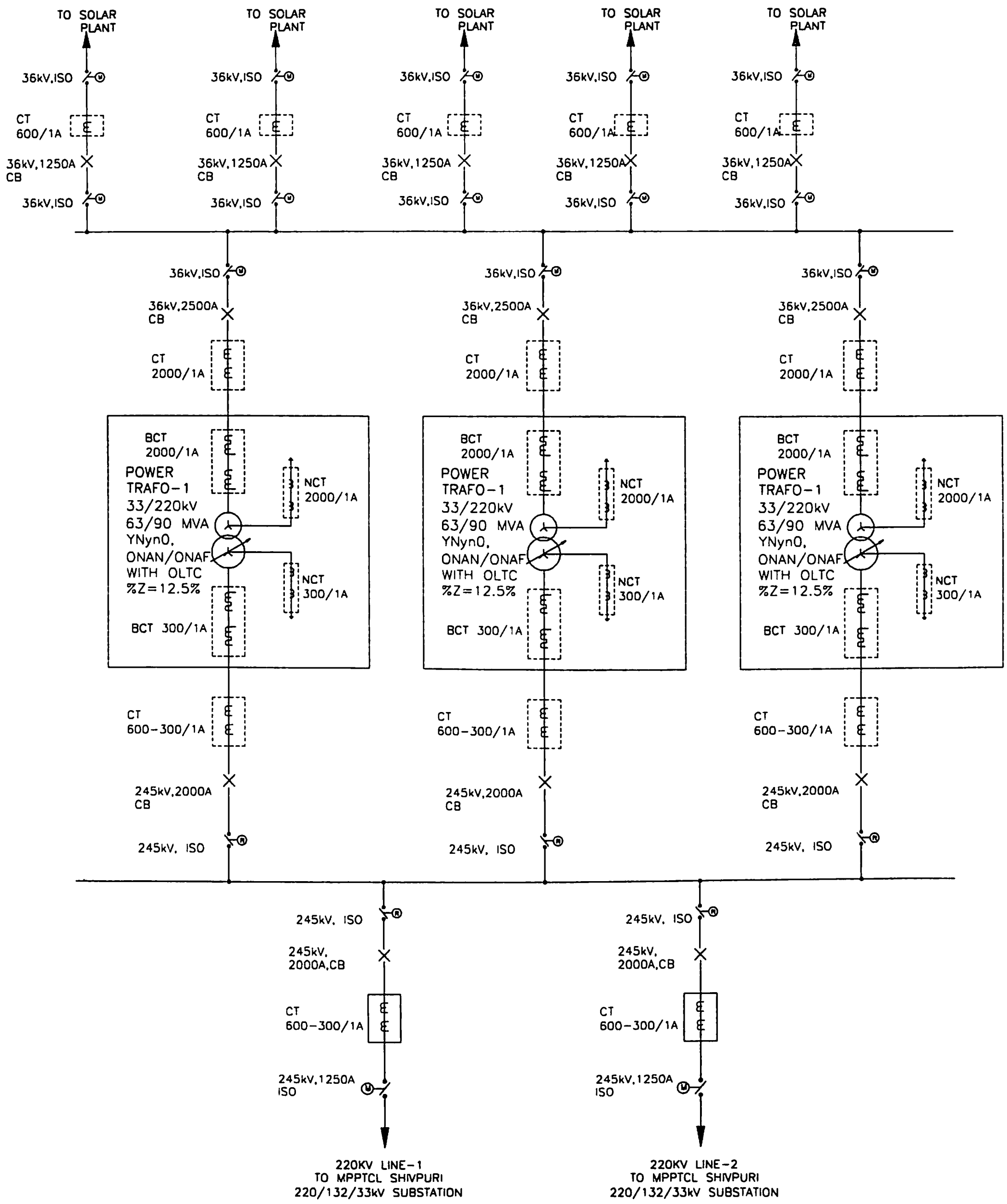


Fig-5.1: Single line diagram of 180MW substation proposal-1.

Table-5.1: Costing of 180MW substation proposal-1

WITH 3 X 66/90MVA Transformers								
S.no	Item Description	Qty	Unit Cost of Equipment (In Lacs)	Total Cost of Equipment (In Lacs)	Failure Rate (λ)	Repair time (r)	Down time per Year (λr)	Inherent Availability (Ai)
1	33kV Isolator	3	44000000	132000000	0.001667	1.5	0.003	0.998
2	33kV Circuit Breaker	3			0.026507	7.5	0.199	0.834
3	33kV Current transfomrer	3			0.001333	2	0.003	0.997
4	80/100MVA Power Transformer	3			0.003793	720	2.731	0.268
5	220kV Current transformer	3			0.001333	2	0.003	0.997
6	220kV Circuit breaker	3			0.022000	35	0.770	0.565
	Total			**132000000**	**0.057**		**3.708**	**0.777**

Proposal-2: In this proposal we have considered 2 number of 33/220kV, 80/100 MVA transformers and associated switchgear equipment (shown in Fig-5.2 single line diagram of 180MW substation proposal-2). Keeping the costs of 33kV (From Inverters to 33kV Bus) system and 220kV system (From 220kV bus to 220kV Grid) constant.

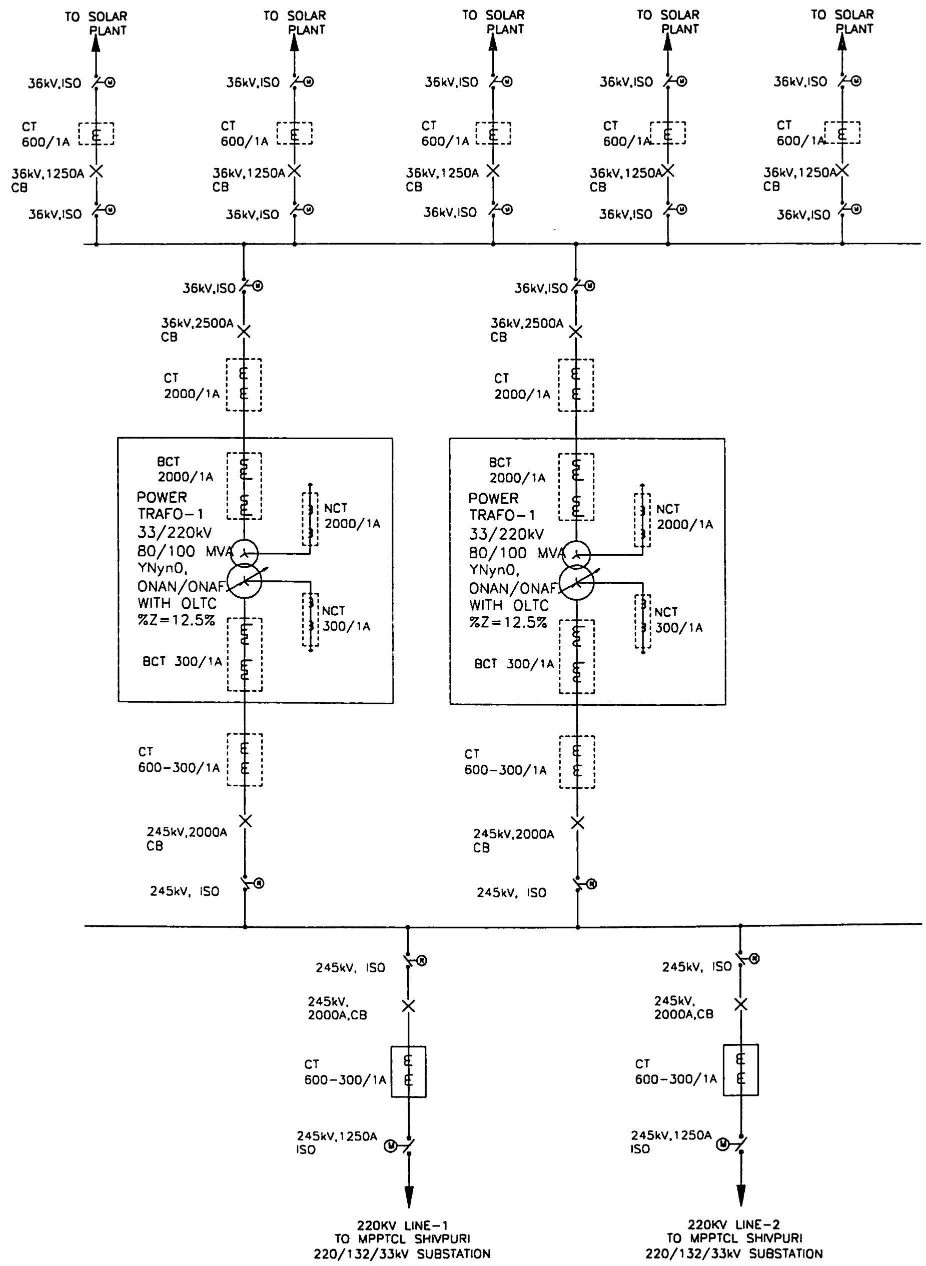


Fig-5.2: Single line diagram of 180MW substation proposal-2

Table-5.2: Costing of 180MW substation proposal-2

WITH 2 X 80/100MVA Transformers								
S.no	Item Description	Qty	Unit Cost of Equipment (In Rs)	Total Cost of Equipment (In Rs)	Failure Rate (λ)	Repair time (r	Down time per Year (λr)	Inherent Availability (Ai)
1	33kV Isolator	2	52500000	105000000	0.003	3	0.008	0.993
2	33kV Circuit Breaker	2			0.040	15	0.596	0.626
3	33kV Current transformer	2			0.002	4	0.008	0.992
4	80/100MVA Power Transformer	2			0.006	1440	8.194	0.109
5	220kV Current transformer	2			0.002	4	0.008	0.992
6	220kV Circuit breaker	2			0.033	70	2.310	0.302
	Total			**105000000**	**0.085**		**11.124**	**0.669**

5.2. Minimum Revenue Requirement Method(MRR):

It was pointed out that there are several acceptable ways of accomplishing the detailed economic analysis for evaluation of systems with varying degrees of reliability. One of those considered acceptable, the RR method was presented in detail and this method will be used in the analysis of two proposals. The two proposal systems included are:

Proposal 1 – Evacuation of 180MW with 3 nos. of 60/80MVA power transformers.

Proposal 2 – Evacuation of 180MW with 2 nos. of 80/100MVA power transformers.

The expected failures per year and the average downtime per year for each of the proposals is tabulated below. These data will be used to show which of the proposals has the MRR making allowances for:

a) Plant start-up time
b) Revenues lost
c) Variable expenses saved
d) Variable expenses incurred
e) Investment
f) Fixed investment charges

One of the benefits of such a rigidly structured analysis is that the presentation is made in a sequential manner utilizing cost/failure data prepared with the assistance of management. With this arrangement, the results of the evaluation are less likely to be questioned than if a less sophisticated method was used.

5.3. Implementation of MRR method

Parameters:

- r - Component repair time or transfer time to restore service, whichever is less, hours power failure
- s - Plant start-up time, hours per failure
- *gp* - Revenues lost per hours of plant down- time, rupees/hour
- x*p* - Variable expenses saved, rupees/hour
- x*i* - Variable expenses incurred per failure, Rupees/failure

C - Investment (installed costs)

λ - Failure rate per year

F - Fixed investment charge factor, per year

Table 5.3 - Reliability economics of proposed systems

		Proposal-1	Proposal-2
1	r - Component repair time or transfer time to restore service, whichever is less, hours power failure	65.05	130.82
2	s - Plant start-up time, hours per failure	0.33	0.33
3	r + s	65.35	131.15
4	g_p - Revenues lost per hours of plant down-time, rupees/h	5,40,400	5,40,000
5	x_p - Variable expenses saved, rupees/h	0	0
6	$g_p - x_p$	5,40,000	5,40,000
7	$(g_p - x_p)(r+s)$ = Rupees/failure	3,52,89,000	7,08,21,000
8	x_i - Variable expenses incurred per failure, Rupees/failure	1,50,000	1,50,000
9	Item (7) + (8) Rupees/failure	3,54,39,000	7,09,71,000
10	λ = failure rate per year	0.057	0.085
11	Item (9) x (10), X Rupees/year	20,20,023	60,32,535
12	C - Investment (installed costs)	13,20,00,000	10,50,00,000
13	F - Fixed investment charge factor, per year	0.40	0.40
14	CF = Fixed investment charges, Rupees/year	5,28,00,000	4,20,00,000
15	$G = X + CF$ (Items (11) + (14)], MRR, Rupees/year	5,48,20,023	4,80,32,535
	Economic choice		**Proposal-2**

Chapter-6

6.1. Conclusion and future scope:

By considering the cost of 33kV (From Inverters to 33kV Bus) system and 220kVsystem (From 220kV bus to 220kV Grid) constant for both the proposals, Proposal-2 is more economic (including capital cost, variable cost and power outage cost) choice than proposal-1. Though proposal-1 is reliable than proposal-2, we have chosen proposal-2 based on proven economic study.

We can extend the above study to overall plant (Starting from Solar modules to available grid) to get accurate economic analysis which will give increased returns to the stakeholders.

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