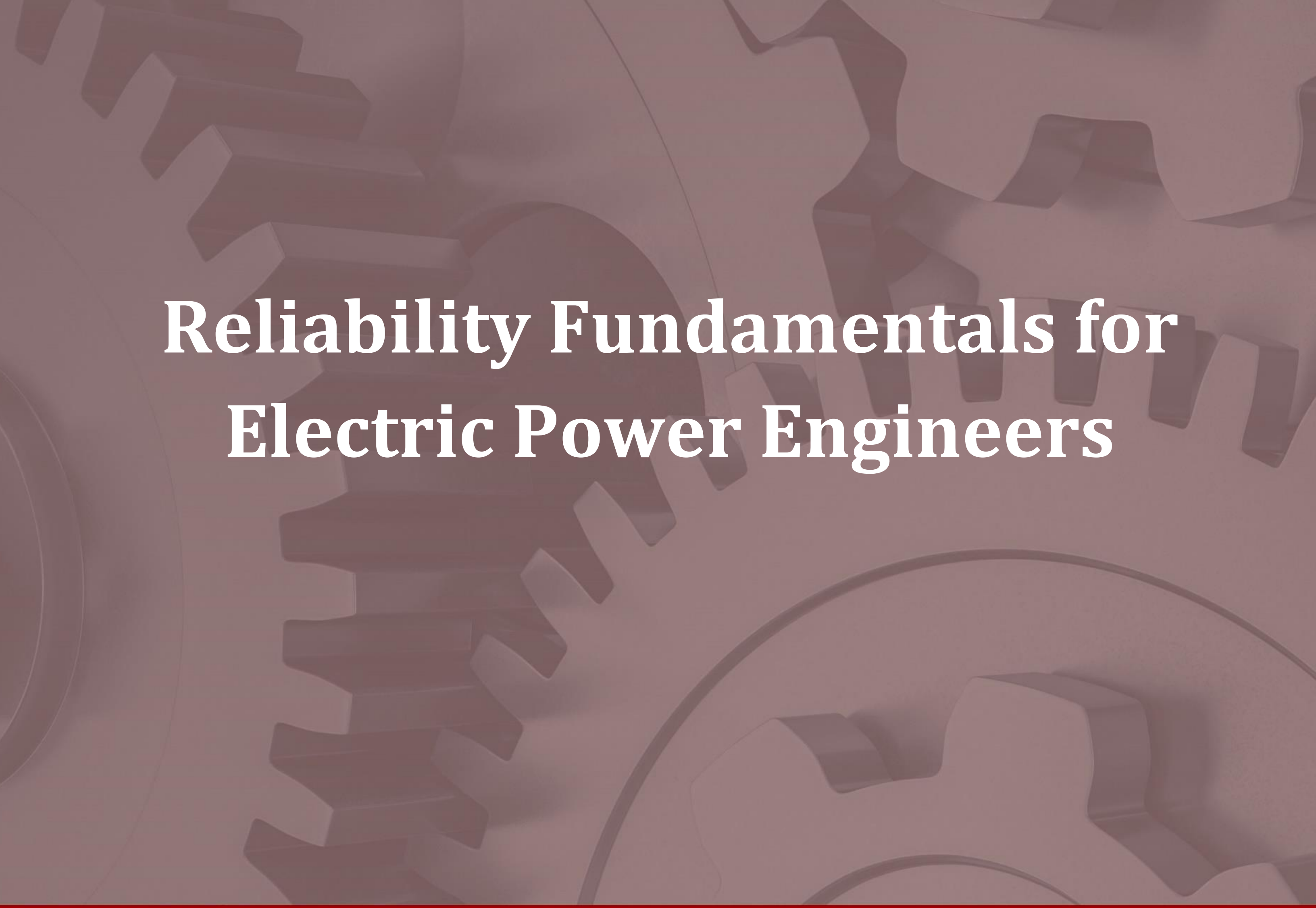

Reliability Fundamentals for Electric Power Engineers

An Online Continuing Education Course for Engineers

Course Number: E-4001

Credit: 4 Hours / 4 PDH / 4 CPD

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Introduction

Reliability is a characteristic of power systems that is reasonably well understood at the qualitative level. In this course, you will learn how to assess power system reliability quantitatively, and how to interpret the results of this numerical understanding of reliability.

This course will give you an introduction to the fundamental concepts of reliability technology as applied to electric power systems serving industrial and commercial facilities. Because it is not possible to talk about the reliability without looking at the reliability of the electric utility system that supplies these installations, we will also have to spend some time with the techniques used to assess reliability of larger systems as well.

The intention of this course is to expose you to the fundamentals of reliability technology. While we will look at some of the techniques used to analyze system reliability from an analytical perspective, it is not a practical option to focus on any of the software tools that are used to perform these calculations in production work. Therefore, while you should expect to come away from this course with an understanding of the principles involved in reliability analysis, you will be on your own to develop familiarity with software applications.

What is Reliability?

In general terms, reliability is a property of a system that describes the likelihood that the system will successfully perform as intended. In the most exact terms, *reliability is the statistical probability that the system will be able to perform its intended mission*. There are several very important notions buried in this definition.

First, it is very important to understand that at its most fundamental level, reliability is probabilistic. That means that the knowledge that an assessment of the reliability of a system gives us is not an absolute assurance of how that system is going to perform, but rather it helps us to understand what we should expect in the way of performance. And as we will see, the stochastic nature of reliability is also a major factor in the data that we have to use in assessing the reliability of a system.

Second, reliability is defined with respect to a specific mission. Defining the mission is sometimes a challenge. Consider an example that is close to the heart of many electrical engineers – a brewery. A brewery consists of a collection of motor-driven pumps, fans, refrigeration systems, automation, heating, and lighting – a whole lot of stuff. And each of those components is critical in its own way. But taken together, they form a singular industrial process, and when we look at reliability we have to look at the totality of the system rather than the components.

Third, no matter how insistent the management of the business may be, 100% reliability is never possible. Reliability analysis can be used as a tool to aid design and operation of a system, and can help improve reliability dramatically. 100% reliability is a mythical concept that simply doesn't exist in the real world. Failures are always possible.

What is Availability?

The notion of "reliability" is more mathematical than physical. We need something that has a more concrete physical meaning in order to apply the concepts to the real world where we live and work. That's where availability comes in.

When applied to the specific case of power systems, availability is the fraction of time that we can reasonably expect that power will be available to support the designed mission or process.
If Uptime is the time that the system is fully operable, and DOWNtime is the time when operation has been disrupted either by stochastic failure or planned outage,

$$\text{Availability} = \frac{\text{System UPtime}}{\text{System UPtime} + \text{System DOWNtime}}$$

Because we are dealing with statistical phenomena and concepts, we have to be careful to define availability as the long-term average up time rather than the duration of a single period of satisfactory performance. And this long-term average is our reasonable expectation of uptime based on our knowledge of the statistical history of the system and its components. Numerically, availability is expressed as a percentage, e.g., 98% availability means that we can expect that power will be available 98% of the time, or conversely, that it will be unavailable 2% of the time.

The availability of practical power installations is quite high, so much so that it has become common to talk about availability in terms of the number of "nines" rather than specific percentages. For example:

"Nines"	Availability, %	Uptime, hours/year	Downtime, hours/year
3	99.9	8751.24	8.76
4	99.99	8759.12	0.876
5	99.999	8759.912	0.0876
6	99.9999	8759.991	0.00876

Take for example the case of "5-nines". This level of availability means that power will be unavailable only 0.0876 hours out of an average year. That translates into 5.25 minutes of downtime. Going to the next level of "6-nines" means that the allowable downtime cannot exceed 31.5 seconds per average year. So when you hear people talking about "nigh nines" reliability, you know that they are imposing some pretty stringent requirements on continuity of service.

First Principles of Reliability: Failure Rate and Repair Time

While knowing the reliability of a system, or perhaps better, the availability of the system, helps us understand how well that system will support the mission of the industrial or commercial facility to which it is dedicated, we need to start our understanding at a more fundamental level. There are two parameters that have the advantage that they can be defined for individual components, and then by application of some analytical techniques, it is possible to extrapolate them to the entire system.

Before getting into the parameters, it is important to clarify that there are three distinct phases in the life of a piece of equipment. In the days to weeks immediately after commissioning, the equipment may experience problems related to how it was initially installed, or that reflect manufacturing defects. This is sometimes referred to as the "infant mortality" period and tends to wash out after a few months. Some cynical engineers have observed that infant mortality ends when the equipment warranty expires.

At the opposite in the life cycle the equipment starts to show signs of wear indicating that its useful life is approaching its end. This time can be deferred by maintenance, but it never goes away entirely. This is referred to as the “wear-out” period.

Failures during both infant mortality and wear-out do not follow a predictable pattern. Fortunately, however, infant mortality and wear-out normally comprise a small fraction of the life cycle of the equipment. When we study reliability, we focus our attention on what happens between these extremes when the probability of failure is predictable and constant.

The first of these parameters is failure rate. Reliability engineers traditionally use the Greek letter λ to designate failure rate. The formal definition of failure rate is

> λ is the expected number of failures per unit of exposure time

Practically, if data is available on a population of similar devices, the average device failure rate can be calculated as

$$\lambda = \frac{\text{number of observed failures in the population}}{\text{total unit - years of experience in the population}}$$

Systems, as well as the components that comprise those systems, have a variety of ways they can fail, and in an exhaustive study of reliability, it is important to identify each failure mode separately along with its associated λ. Consider the case of a circuit breaker – there are some failures in which the circuit breaker opens incorrectly, causing an interruption in power flow. But there are also failures in which that same circuit breaker fails to close upon command – that also causes an interruption in power flow, but the significance of the failure in the context of the total system depends on what is happening with other components. Here, for the sake of keeping this a “Reliability Fundamentals” course, we will simply lump all failures together under one black cloud.

We may, however, want to segregate forced failures (sometimes referred to as ‘stochastic failures” because they are presumed to occur randomly) from planned, or maintenance-related outages. Obviously, an outage is an outage, and the net effect is the same – an outage means that power is unavailable.

If λ is the number of failures per unit of time, then 1/λ is the expected mean time to failure expressed in compatible units. For example, if the failure rate of a transformer is 0.013 per year, then the expected mean time to failure of that transformer is 1/0.013, or 76.92 years.

The second critical parameter is the mean downtime per failure. This is commonly denoted using the Greek letter ρ. The strict definition of downtime

> ρ is the average time to replace or restore the system following a failure

ρ is also sometimes referred to as the Mean Time to Repair, or MTTR. Obviously, ρ can be defined for both stochastic events and maintenance events. It can also have different values for different kinds of failures.

Referring to the data on a population of devices, the downtime per failure can be calculated as

$$\rho = \frac{\text{total hours of downtime in the population}}{\text{total number of failure events}}$$

Related to these two parameters is a third metric that we will find very useful. Mean time to failure (MTTF) is the average exposure time between the initiations of failure events. There is also a mean time between failures (MTBF), which is the average exposure time between when a repair is made and when the next failure can be expected to occur. MTBF is the overall system uptime. As a practical matter, however, if the availability of the system is high, MTTF and MTBF are very nearly the same.

Therefore, we can also say

$$\text{Availability} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} = \frac{1/\lambda}{1/\lambda + \rho}$$

One precaution is important – for this expression to be true, it is important that the units of λ and ρ be compatible. It is typical to find λ expressed as failures per year, while ρ is often listed in tables as hours per failure. Therefore, it is necessary that either λ be converted to failures per hour, or that ρ be expressed as years per failure in order to calculate availability in this fashion. Regardless of which way you choose, you will need to know that there are 8760 hours per year.

Systems versus Components

The objective of performing a reliability analysis of a system is to determine how that system will perform in supporting the requirements of the designated load (i.e., the "mission"). In order to assess the system, it is necessary to start with the components that comprise the system.

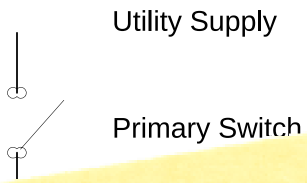
That said, it is sometimes a challenge to figure out how much component granularity is required to perform the analysis. A practical power system is comprised of a number of discrete components – transformers, circuit breakers, fuses, overhead lines, cables, etc. Each of these discrete components can be further broken down into subsets of components. Obviously, it's easy to become overwhelmed by details.

As in the case of linear circuit analysis, some very good advice here is to only include detail that actually provides insight into the performance being studied. For example, a medium-voltage circuit breaker physically consists of a bus structure, an interrupting device and associated stored-energy mechanism, various intelligent control devices (protection relays), sensors (instrument transformers), and a host of auxiliary devices that bring all of the major pieces together. If one is concerned about the reliability of a circuit breaker, it may well be necessary to investigate all of these components, but if the focus is on the performance of an overall system, visualizing the breaker itself as the lowest level component may be adequate.

As a practical matter, it may also be impossible for the system-level analyst to find credible reliability data on the subcomponents comprising the major power system devices.

Finally, the analytical procedures described below are manageable, but can quickly become very tedious as the number of components in the system increases. So once again, there is an incentive to keep things simple by focusing only on the most pertinent components.

Let’s take an example. Figure 1 shows a typical service entrance for a light industrial or commercial facility. Power is received from the electric utility through a switching device that may be as simple as a fused-disconnect switch. It is then transformed down to a lower voltage, and passes through a main breaker onto the bus.



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