1

Design and Analyses Concepts of Power Systems

Electrical power systems are the most complex man-made nonlinear systems on earth. Also these are highly dynamic in nature. Consider that the circuit breakers are closing and opening, the generation is varying according to load demand, and the power systems are subjected to disturbances of atmospheric origin and switching operations. The energy state of the power systems is constantly changing and the energy is being redistributed into electromagnetic and mechanical systems.

Yet, we study electrical power systems in the steady state; though, it may last for a short duration. The transition from one steady state to another does not take place instantaneously and transition to each steady state should be acceptable and stable.

The study of power systems in steady-state amounts to taking a still picture of continuously varying natural phenomena like sea waves. The study of transients that lead from one steady state to another requires transient analysis. The four volumes of this series present steady-state analysis of power systems for the material covered in these volumes. However, the transient analysis is presented as required. There cannot be a water tight compartment between the steady state and the transient state—one may lead to another. For example, short circuits in AC systems are decaying transients and subject the power system to severe stresses and stability problems, yet empirical calculations as per standards are applied for their calculations.

However, this series does not provide an insight into the transient behavior of the power systems and confines the analyses *mostly* to steady state. Some sporadic reference to transients may be seen in some chapters and appendices of the book. A section on effect of protective relaying on stability and fundamental concepts of power system stability are included in Volume 4.

The time duration (frequency) of the transient phenomena in the power system varies. The International Council for Large Electrical Power Systems (CIGRE) classifies the transients with respect to frequency in four groups. These groups are low-frequency oscillations (0.1 Hz–3 kHz), slow front surges (50/60 Hz–20 kHz), fast front surges (10 kHz–3 MHz), and very fast front surges (100 kHz–50 MHz). It is very difficult to develop a power system component (say transmission lines) model, which is accurate from low to very high frequencies. Thus, models are good for a certain frequency range. A model must reproduce the frequency variations, saturation, nonlinearity, surge arrester characteristics, power fuse, and circuit breaker operations accurately for the frequency range considered. The models in this book are mostly steady-state models. For harmonic analysis, the impacts of higher frequencies involved on some component models are discussed in Volume 3.

1.1 Static and Dynamic Systems

A time-invariant resistor connected to a sinusoidal source takes a current depending on the value of the resistor and the applied voltage. The output, the voltage across the resistor, is solely dependent on the input at that instant. Such a system is *memoryless* and is a static system. The energy is dissipated as heat.

On the other hand, a capacitor or an inductor is not memoryless. Figure 1.1 shows a resistor and a capacitor connected to a voltage source. For the resistor at any time: $e(t) = R \times i(t)$. For the capacitor

$$e(t) = e(t_0) + \int_{t_0}^{t} i(t)\,\mathrm{d}t \tag{1.1}$$

The output depends not only on the input from t_0 to t but also on the capacitor voltage at t_0 due to the past current flow.

The state of the system with memory is described by *state variables* that vary with time (see Section 1.2). The state transition from $\mathbf{x}(t_0)$ at time t_0 to $\mathbf{x}(t)$ at time $t > t_0$ is a dynamic process that can be described by differential equations or difference equations:

$$\begin{aligned} \frac{\mathrm{d}x}{\mathrm{d}t} &= \frac{1}{C} r(t) \\ r(t) &= i(t) \end{aligned} \tag{1.2}$$

We defined a dynamic system as the one whose behavior changes with time. Neglecting wave propagation and assuming that the voltages and currents external to the system are bounded functions of time; a broad definition can be that a dynamic circuit is a network of n-terminal resistors, capacitors and inductors, which can be nonlinear. We call a capacitor and an inductor as dynamic elements. We can define the nonlinear resistors, inductors, and capacitors using the following equations:

$$\begin{aligned} R(v, i) &= 0 \\ C(q, \upsilon) &= 0 \\ L(\phi, i) &= 0 \end{aligned} \tag{1.3}$$

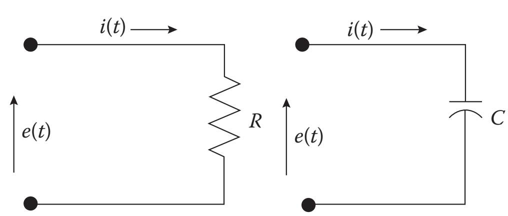

FIGURE 1.1
A resistor and capacitor connected to a voltage source—to illustrate memoryless and systems with memory.

These relations are *constituency relations*. A nonlinear resistor is described by the current and voltage and a nonlinear capacitor by the charge q and voltage v across it. If an element is time varying, we write

$$\begin{aligned} &R(\upsilon, i, t) = 0 \\ &C(q, \upsilon, t) = 0 \\ &L(\phi, i, t) = 0 \end{aligned} \tag{1.4}$$

A resistor is voltage controlled, if the current i is a function of the voltage across it. The constituency relation written as $R(i,v) = 0$ is expressed as follows:

$$i = \hat{i}\upsilon \tag{1.5}$$

If it is current controlled, we write as follows:

$$\upsilon = \hat{\upsilon} i \tag{1.6}$$

Same notations apply to capacitors and inductors. For a capacitor, we write as follows:

$$\begin{aligned} &C(q, \upsilon) = 0 \quad \text{or} \quad q = \hat{q}\upsilon \text{ (voltage controlled).} \\ &\upsilon = \hat{\upsilon} q \text{ (charge controlled)} \end{aligned} \tag{1.7}$$

And for an inductor

$$i = \hat{i}(\phi) \quad \phi = \hat{\phi}(i) \tag{1.8}$$

A nonlinear resistor with constituency relationship $i = g(\nu)$ is passive, if $\nu g(\nu) \geq 0$ for all v. It is strictly passive if $\nu g(\nu) > 0$ for all $\nu \neq 0$. It is eventually passive if there exists a $k > 0$ such that $\upsilon g(\upsilon) \geq 0, |\upsilon| > k$. It is strictly passive if $\upsilon g(\upsilon) > 0, |\upsilon| > k$.

$$\upsilon g(\upsilon) \geq 0, |\upsilon| > k \tag{1.9}$$

1.2 State Variables

When we are interested in terminal behavior of a system, i.e., for certain inputs, there are certain outputs, the system can be represented by a simple box. There can be multiple inputs and outputs, Figure 1.2. The mathematical model specifies the relations between the inputs and outputs:

$$\begin{aligned} &r_i(t),\ t = 1, 2, 3, \ldots m \\ &y_i(t),\ t = 1, 2, 3, \ldots p \end{aligned} \tag{1.10}$$

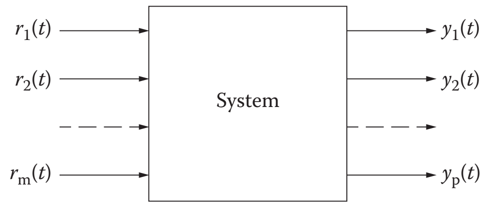

FIGURE 1.2
A system with multiple inputs and outputs.

The response $y_i(t)$ will be a function of initial state vector $x(t_0)$ and the inputs $r_i(t)$ for $t > t_0$ In general, the state of the system at any time is given by $\mathbf{x}(t)$. The components of this vector $x_1(t), x_2(t), \ldots, x_n(t)$ are called the *state variables*.

The input-output-state relations for the system can be represented by the following:

$$\begin{gathered} y_1(t) = \varphi_1\left[x_1(t_0), \ldots, x_n(t_0); r_1(t_0, t), \ldots, r_m(t_0, t)\right]; t \geq t_0 \\ \vdots \\ y_p(t) = \varphi_p\left[x_1(t_0), \ldots, x_n(t_0); r_1(t_0, t), \ldots, r_m(t_0, t)\right]; t \geq t_0 \end{gathered} \tag{1.11}$$

The dependence of $\mathbf{x}(t)$ on $\mathbf{x}_0(t)$ and $r(t_0, t)$ is

$$\begin{gathered} x_1(t) = \phi_1\left[x_1(t_0), \ldots, x_n(t_0); r_1(t_0, t), \ldots., r_m(t_0, t)\right]; t \geq t_0 \\ \vdots \\ x_n(t) = \phi_n\left[x_1(t_0), \ldots, x_n(t_0); r_1(t_0, t), \ldots., r_m(t_0, t)\right]; t \geq t_0 \end{gathered} \tag{1.12}$$

In matrix form

$$\begin{gathered} \mathbf{x}(t) = \begin{vmatrix} x_1(t) \\ x_2(t) \\ . \\ x_n(t) \end{vmatrix} \quad \phi(.) = \begin{vmatrix} \phi_1(.) \\ \phi_2(.) \\ . \\ \phi_n(.) \end{vmatrix} \quad \mathbf{y}(t) = \begin{vmatrix} y_1 \\ y_2 \\ . \\ y_p \end{vmatrix} \quad \phi(.) = \begin{vmatrix} \varphi_1(.) \\ \varphi_2(.) \\ . \\ \varphi_p(.) \end{vmatrix} \\ \mathbf{x}(t_0) = \begin{vmatrix} x_1(t_0) \\ x_2(t_0) \\ . \\ x_n(t_0) \end{vmatrix} \quad \mathbf{r}(t_0, t) = \begin{vmatrix} r_1(t_0, t) \\ r_2(t_0, t) \\ . \\ r_m(t_0, t) \end{vmatrix} \end{gathered} \tag{1.13}$$

In abbreviated form

$$\begin{gathered} \mathbf{x}(t) = \phi\left[\mathbf{x}(t_0), \mathbf{r}(t_0, t)\right]; \quad t \geq t_0 \\ \mathbf{y}(t) = \varphi\left[\mathbf{x}(t_0), \mathbf{r}(t_0, t)\right]; \quad t \geq t_0 \end{gathered} \tag{1.14}$$

Figure 1.3 shows the concept of state variables in a general system.

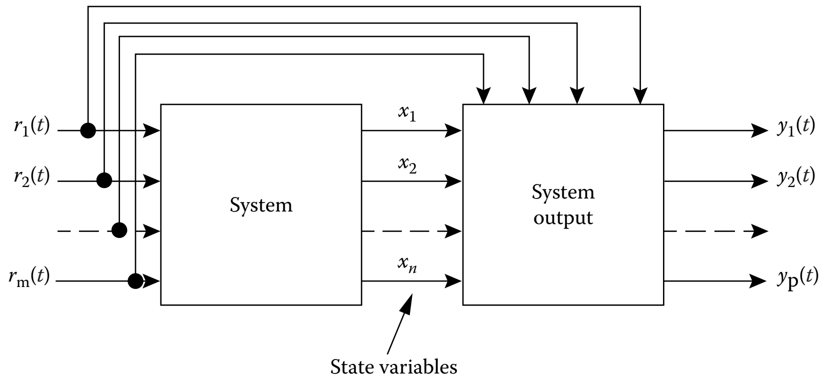

FIGURE 1.3
A general system to show state variables.

1.3 Linear and Nonlinear Systems

It is pertinent to define mathematically linearity and nonlinearity, static, and dynamic systems.

Linearity implies two conditions:

1. Homogeneity
2. Superimposition

Consider the state of a system defined by the following:

$$\dot{\mathrm{x}} = \mathrm{f}\left[\mathrm{x}(t),\ \mathbf{r}(t), t\right] \tag{1.15}$$

If $\mathbf{x}(t)$ is the solution to this differential equation with initial conditions $x(t_0)$ at $t = t_0$ and input $\mathbf{r}(t)$, $t > t_0$:

$$\mathrm{x}(t) = \phi\left[\mathrm{x}(t_0), \mathbf{r}(t)\right] \tag{1.16}$$

Then, homogeneity implies that

$$\phi\left[\mathrm{x}(t_0), \alpha\mathbf{r}(t)\right] = \alpha\phi\left[\mathrm{x}(t_0), \mathbf{r}(t)\right] \tag{1.17}$$

where α is a scalar constant. This means that $\mathbf{x}(t)$ with input $\alpha\mathbf{r}(t)$ is equal to α times $\mathbf{x}(t)$ with input $\mathbf{r}(t)$ for any scalar α.

Superposition implies that

$$\phi\left[\mathrm{x}(t_0), \mathbf{r}_1(t) + \mathbf{r}_2(t)\right] = \phi\left[\mathrm{x}(t_0), \mathbf{r}_1(t)\right] + \phi\left[\mathrm{x}(t_0), \mathbf{r}_2(t)\right] \tag{1.18}$$

That is, $\mathbf{x}(t)$ with inputs $\mathbf{r}_1(t)+\mathbf{r}_2(t)$ is = sum of $\mathbf{x}(t)$ with input $\mathbf{r}_1(t)$ and $\mathbf{x}(t)$ with input $\mathbf{r}_2(t)$. Thus, linearity is superimposition plus homogeneity.

1.3.1 Property of Decomposition

A system is said to be linear if it satisfies the decomposition property and the decomposed components are linear.

If $x'(t)$ is the solution of Equation 1.14 when system is in zero state for all inputs $\mathbf{r}(t)$, i.e.,

$$x'(t) = \phi(0, \mathbf{r}(t)) \tag{1.19}$$

And $\mathbf{x}''(t)$ is the solution when all states $x(t_0)$, the input $\mathbf{r}(t)$ is zero, i.e.,

$$x''(t) = \phi(x(t_0), 0) \tag{1.20}$$

Then, the system is said to have decomposition property, if

$$x(t) = x'(t) + x''(t) \tag{1.21}$$

The zero-input response and zero-state response satisfy the property of homogeneity and superimposition with respect to initial states and initial inputs, respectively. If this is not true then the system is nonlinear.

For nonlinear systems, general methods of solutions are not available and each system must be studied specifically. Yet, we apply linear techniques of solution to nonlinear systems over a certain time interval. Perhaps the system is not changing so fast, and for certain range of applications, linearity can be applied. Thus, the linear system analysis forms the very fundamental aspect of the study.

For the short-circuit calculations, we assume that the system components are linear. In load flow, the voltage drop across a reactor on flow of reactive current is nonlinear, and iterative techniques are applied. For the harmonic penetration, the system components have nonlinear relation with respect to frequency.

1.4 Linearizing a Nonlinear System

In electrical power systems, to an extent all system components can be considered nonlinear. Saturation, fringing, eddy current and proximity effects, thermal effects, especially at high frequency, cannot be ignored. This becomes of special importance for switching transient studies. Handling nonlinearity requires knowledge of

- Piecewise linearization, one example is saturation in transformers
- Exponential segments method is used in arrester models
- One-time step delay methods are used in pseudo-nonlinear devices
- Iterative Newton methods are discussed in Volume 2

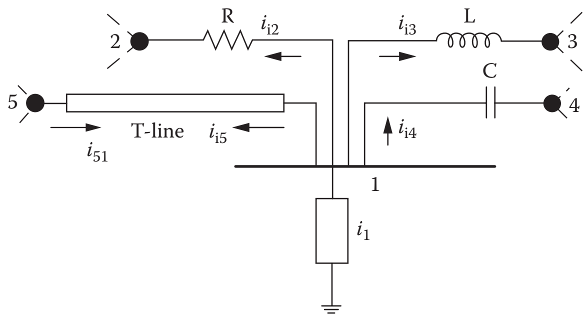

FIGURE 1.4
A node (Bus1) with multiple connections and current injections—to illustrate nonlinearity models.

- Trapezoidal rule of integration
- Runge–Kutta methods
- Taylor series and approximations

These techniques are not discussed. Consider a network of connections as shown in Figure 1.4. For the inductance branch, nodes 1 and 3, we can write as follows:

$$\upsilon = L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{1.22}$$

In terms of difference equation

$$\frac{\upsilon(t)+\upsilon(t-\Delta t)}{2} = L\frac{i(t)-i(t-\Delta t)}{\Delta t} \tag{1.23}$$

This can be written as follows:

$$i_{13}(t) = \frac{\Delta t}{2L}\left(\upsilon_1(t)-\upsilon_3(t)\right) + hist_{13}(t-\Delta t) \tag{1.24}$$

where $hist_{13}$ term is known from the preceding time step.

$$hist_{13}(t-\Delta t) = i_{13}(t-\Delta t) + \frac{\Delta t}{2L}\left(\upsilon_1(t)-\upsilon_3(t)\right) \tag{1.25}$$

For the capacitance circuit, we can similarly write as follows:

$$hist_{14}(t-\Delta t) = -i_{14}(t-\Delta t) - \frac{2C}{\Delta t}\left(\upsilon_1(t-\Delta t)-\upsilon_4(t-\Delta t)\right) \tag{1.26}$$

For the transmission line, ignoring losses

$$
\begin{aligned}
i_{15}(t) &= \frac{1}{Z}\upsilon_1(t) + hist_{15}(t-\tau) \\
hist_{15}(t-\tau) &= -\frac{1}{Z}\upsilon_5(t-\tau) - i_{51}(t-\tau)
\end{aligned}
\tag{1.27}
$$

where Z = surge impedance and τ = line length/velocity of propagation. Therefore, for node 1, we can write as follows:

$$
\begin{aligned}
&\left(\frac{1}{R}+\frac{\Delta t}{2L}+\frac{2C}{\Delta t}+\frac{1}{Z}\right)\upsilon_1(t) - \frac{1}{R}\upsilon_2(t) - \frac{\Delta t}{2L}\upsilon_3(t) - \frac{2C}{\Delta t}\upsilon_4(t) \\
&= i_1(t) - hist_{13}(t-\Delta t) - hist_{14}(t-\Delta t) - hist_{15}(t-\tau)
\end{aligned}
\tag{1.28}
$$

For any type of network with n nodes, we can write the general equation as follows:

$$\bar{G}\bar{v}_t = \bar{i}_t - \overline{hist} \tag{1.29}$$

where
$\bar{G}$ = nxn symmetrical nodal conductance matrix,
$\bar{v}_t$ = vector of n node voltages,
$\bar{i}_t$ = vector of current sources,
$\overline{hist}$ = vector of n known history terms.

Some nodes will have known voltages or may be grounded. Equation 1.29 can be partitioned into set of nodes A with known voltages and a set B with unknown voltages. The unknown voltages can be found by solving for $\bar{\upsilon}_{At}$

$$\bar{G}_{AA}\bar{\upsilon}_{At} = \bar{i}_{At} - \overline{hist}_A - \bar{G}_{AB}\bar{\upsilon}_{Bt} \tag{1.30}$$

Example 1.1

Consider a function as depicted in Figure 1.5. The relation is nonlinear but continuous. At point P, a tangent can be drawn and the small strip around P can be considered a linear change in the system. Let the function be represented by the following:

$$y = \varphi(r) \tag{1.31}$$

Expand according to Taylor's series:

$$y = \varphi(r) = \varphi(r_0) + \left(\frac{d\varphi}{dr}\right)_0 \frac{(r-r_0)}{1!} + \left(\frac{d^2\varphi}{dr^2}\right)_0 \frac{(r-r_0)^2}{2!} + \cdots \tag{1.32}$$

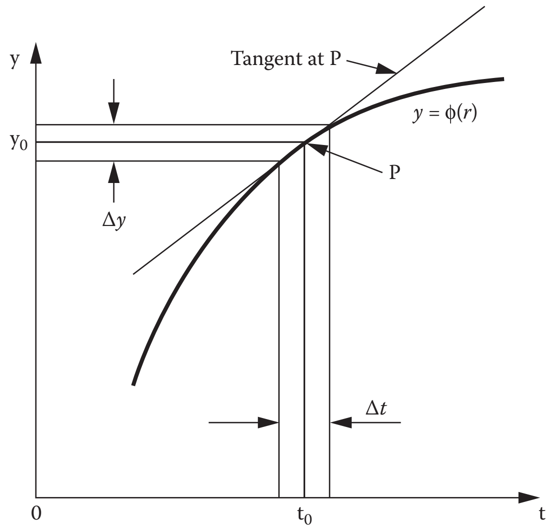

FIGURE 1.5
Linearizing a nonlinear system with Taylor's series.

As the variation at point P is small, neglect the higher order terms in Taylor's series:

$$y = \varphi(r) = \varphi(r_0) + \left(\frac{d\varphi}{dr}\right)_0 \frac{(r - r_0)}{1!} = y_0 + m(r - r_0) \tag{1.33}$$

where m is the slope at the operating point.

This forms the basic concept of load flow with Newton Raphson method, Volume 2.

1.5 Time-Invariant Systems

When the characteristics of a system do not change with time it is called a time-invariant system. If these change with time the system is time-variant.

Figure 1.6a represents a time-invariant system whereas Figure 1.6b does not represent a time-invariant system. Mathematically, the operator $Z^{-\tau}$ acting on the system results in an advancement and retardation without impacting the shape of the signal:

$$\begin{aligned} Z^{\tau}[f(t)] &= f(t+\tau) \\ Z^{-\tau}[f(t)] &= f(t-\tau) \end{aligned} \tag{1.34}$$

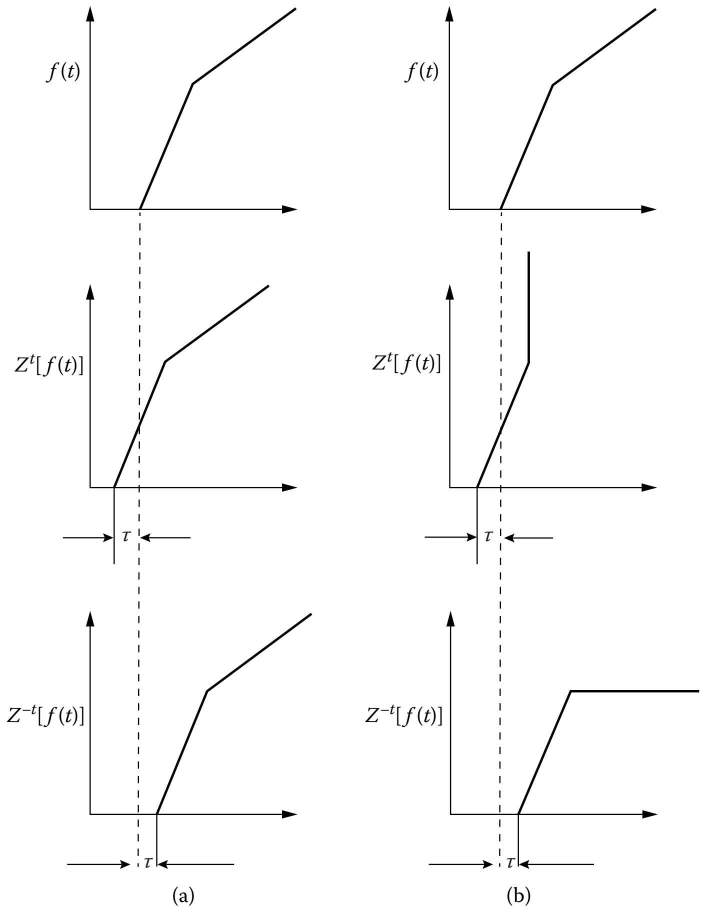

FIGURE 1.6
The effect of translation operator on a (a) time-invariant system and (b) nontime-invariant system.

The state variable model of a time-invariant system can be written as follows:

$$\begin{vmatrix} \dot{x}_1 \\ \dot{x}_2 \\ . \\ \dot{x}_n \end{vmatrix} = \begin{vmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{22} & . & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & . & a_{nn} \end{vmatrix} \begin{vmatrix} x_1 \\ x_2 \\ . \\ x_n \end{vmatrix} + \begin{vmatrix} b_{11} & b_{12} & . & b_{1m} \\ b_{21} & b_{22} & . & a_{2m} \\ . & . & . & . \\ b_{m1} & b_{m2} & . & a_{mm} \end{vmatrix} \begin{vmatrix} r_1 \\ r_2 \\ . \\ r_m \end{vmatrix} \tag{1.35}$$

and

$$\begin{vmatrix} y_1 \\ y_2 \\ . \\ y_p \end{vmatrix} = \begin{vmatrix} c_{11} & c_{12} & . & c_{1n} \\ c_{21} & c_{22} & . & c_{2n} \\ . & . & . & . \\ c_{p1} & c_{p2} & . & c_{pn} \end{vmatrix} \begin{vmatrix} x_1 \\ x_2 \\ . \\ x_n \end{vmatrix} + \begin{vmatrix} d_{11} & d_{12} & . & d_{1m} \\ d_{21} & d_{22} & . & d_{2m} \\ . & . & . & . \\ d_{p1} & d_{p2} & . & d_{pm} \end{vmatrix} \begin{vmatrix} r_1 \\ r_2 \\ . \\ r_m \end{vmatrix} \tag{1.36}$$

The state variables are a linear combination of system states and inputs and similarly output is a linear combination of states and inputs. Or in the abbreviated form

$$\begin{aligned} \dot{x} &= Ax + Br \quad \text{state equation} \\ y &= Cx + Dr \quad \text{output equation} \end{aligned} \tag{1.37}$$

Here, **x** = n-dimensional state vector, **r** = m-dimensional input vector, **y** = p-dimensional output vector, **A** = nxn square matrix, **B** = nxm matrix, **C** = pxn matrix, and **D** = pxm matrix.

1.6 Lumped and Distributed Parameters

Consider a system of circuit elements like resistors, capacitors, and inductors connected in a certain manner, and let us call it a system. A system is called a lumped parameter system if a disturbance or input applied to any point of the system propagates *instantaneously* to all other parts of the system. This is a valid assumption if the physical dimension of the system is small compared to the wavelength of the highest significant frequency. For example, the transmission lines [less than approximately 80 km (50 miles)] can be modeled with lumped parameters without much error. For transient analysis, these systems can be modeled with ordinary differential equations. The energy is dissipated or stored in isolated components like resistors, inductors, and capacitors.

In a distributed parameter system, it *takes a finite time for an input to travel to another point in the system*. We need to consider the space variable in addition to time variable. The equations describing such systems are partial differential equations.

In power systems, all systems are to an extent distributed systems. A rigorous model of a motor winding will consist of a resistance, inductance, and capacitance and capacitance to ground of each turn of the winding. This model may be required to study the surge phenomena in the motor windings say on impact of a switching surge or lightning impulse.

A long transmission line has resistance, inductance, and capacitance distributed along its length. Wave propagation occurs over long lines even at power frequencies. Figure 1.7 shows

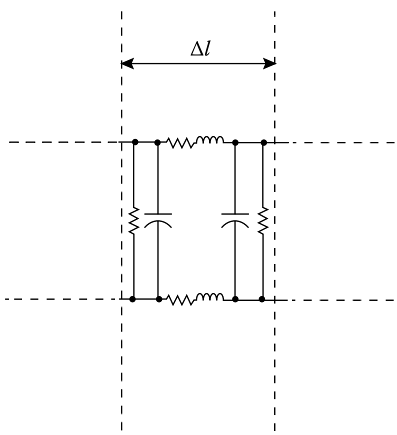

FIGURE 1.7
Lumped equivalent model of a system with distributed parameters.

a small section of a long line, Δl, where the series resistance and inductance and shunt admittance and susceptance are shown lumped. This assumption of lumping is acceptable as the line section consists of a small section Δl, the entire line length being represented with series connections of infinite number of such small sections.

1.7 Optimization

The problem of optimization occurs in power system studies quite often. A solution must optimize between various conditions and constraints. See Volume 2 for optimal power flow and various techniques to reach an optimal solution. We can describe optimization, in general, as a mathematical attempt to find the best solution with interplay of design, available resources, constraints, and costs that is spread over a period of time from a couple of seconds to years. Automatic Generation Control (AGC) must respond fast for system integrity within seconds while optimizing generation planning and minimizing investment, which evolves over the course of years.

1.8 Planning and Design of Electrical Power Systems

The electrical power systems are like a *chain with many complex links*. A weakness in any *chain-link* can jeopardize the integrity of the complete system. In general, the electrical power systems should be

- Secure
- Safe
- Expandable
- Maintainable
- Reliable

A number of criteria apply to the planning and design of electrical systems, namely,

1. All switching devices must be selected to interrupt and withstand system short-circuit currents, Volume 1.
2. All interlocks must guarantee that human errors of operation are eliminated, for example, when switching between sources that may be out of phase, when paralleling two different sources of power, and when bringing another standby source in service.
3. The protective systems should isolate the faulty section without escalating the fault to nonfaulted areas, Volume 4.
4. All system loads must be served without excessive voltage dips and voltage instability under various switching conditions, Volume 2.
5. The steady state and transient stability of the systems must be ensured under the studied upset conditions, Volume 4.

6. The starting of large motors should not create excessive voltage dips and instability.
7. The system and equipment grounding should receive adequate considerations and protections. Proper grounding of equipment (safety grounding) and system neutrals (system grounding) is essential for human safety and ground fault relaying, Volume 4.
8. Proper mitigation of harmonics from nonlinear loads should be provided to meet the required standards and protect electrical equipment from deleterious effects of harmonics, Volume 3.
9. In industrial environment, all electrical equipment should be heavy duty to endure more frequent usage and for reliability. The listed equipment should be provided.
10. A reliability analysis of the distribution system in the design stage should be conducted.
11. Special requirements are applicable for standby and emergency systems, continuity of essential loads on normal power interruption, standby generators and the like.
12. Design of electrical systems for special facilities like hospitals, nuclear plants, generating plants, aircraft hangers, railway electrifications, renewable power sources, interconnections with grid demand special precautions, and analyses. Solar and wind generation plants require specific knowledge of these facilities and electrical and equipment characteristics. Separate set of standards and equipment specifications are applicable to nuclear facilities. *To an extent all power distribution systems even for the same type of facility differ, to meet the specific requirements* and generalizations cannot be applied. Generalization can be a guideline only; and the experience of the Engineer and Planner becomes the prime factor.

This list of tasks for effective planning and development and for meeting the specific performance requirements of electrical power systems can be long—depending upon the electrical power system under consideration.

The integrity of the electrical equipment should be maintained with emphasis on the type of enclosures, insulation coordination, operating mechanisms, grounding and protective relaying. Yet, the power system designs may fall short from engineering design and safety considerations. Even the functionality for which these systems are designed for adequate performance may be compromised.

Though there is a spate of guidelines and standards, it is not unusual to see inadequately designed systems, lacking in some respect or the other. Competition and economical constraints can make even expert designers and planners to cut corners, which may ultimately result in spending more funds for the short-term fixes and long-term upgrades.

The power system studies can be an effective tool in the design of power systems. These can also identify weak spots, limitations of the current systems, and point to remedial measures. For example,

- The switching devices may be underrated from short-circuit conditions.
- The load flow may indicate problems of voltage drops or voltage instability under certain operating and switching conditions.
- The protective relaying may be inadequate; lack of coordination may result in nuisance trips and shutdowns.

- The harmonic pollutions may overload the system components and application of capacitors may result in harmonic resonance problems. The harmonics can seriously derate the cables and transformers and overload the rotating equipment.
- Adequate surge protection may not be provided.
- Considerations may not be applied for transient stability for disturbances and faults in the system.
- The equipment may be underrated to carry the system load currents in one condition or the other.

This series attempts to analyze these problems. The surge protection is not discussed in this series.

1.9 Electrical Standards and Codes

There are a number of current standards and guidelines for planning and designing of electrical power systems for commercial, industrial, and utility applications. IEEE Industry Applications Society and Power Engineering Society have immense database of publications exploring the new technology, drafting new standards, revising the existing standards, and providing guidelines for specifying, engineering, maintenance, equipment selection, and applications. The IEEE website [1] compiles more than three million documents that a user can access,—which includes standards, technical papers in conferences, transactions, and journals. Reference [2] provides titles of IEEE "color books." The electrical requirements of protection, wiring, grounding, control and communication systems, contained in [3] National Electrical Code (NEC) are important for electrical engineers. In most instances, the NEC is adopted by local ordnance as a part of building code. Then, there are numbers of NFPA standards containing requirements on electrical equipment and systems [4], which include NFPA 70E-2015.

Legislation by the US federal government has the effect of giving certain ANSI standards the impact of law. Not all standards are ANSI approved. Occupational safety and Health Administration (OSHA) requirements for electrical systems are contained in 29 CFR Part 1910 of the Federal Register [5].

The US National Institute of Occupational Safety and Health (NIOSH) publish Electrical Alerts to warn unsafe practices of hazardous electrical equipment, [6]. The US Department of Energy has advanced energy conservation standards. These include ASHRA/IES legislation embodying various energy conservation standards, such as ASHRAE/IES 90.1P. These standards impact architectural, mechanical, and electrical designs.

The Underwriters Laboratories (ULs) and other independent testing laboratories may be approved by an appropriate jurisdictional authority like OSHA. A product may be UL labeled or listed. Generally, the designers insist for UL labels on the electrical components in a design and planning process and specifications for the electrical equipment. The UL publishes an Electrical Construction Materials Directory, an Electrical Appliance and Utilization Directory, and other standards. The Electrification Council (TEC) is representative of investor-owned utilities and publishes several informative handbooks [7].

The National Electrical Manufacturer's Association (NEMA) [8] represents the equipment manufacturers and their publications that standardize certain design features of electrical equipment and provide testing and operating standards. NEMA publishes a number of standards on electrical equipment, which contain important application and selection guidelines.

Further, there are many handbooks, which, over the course of years have established reputations in the electrical field; some of these are cited in [9].

Safety for operating personnel is achieved through proper design. The National Electric Safety Code (NESC) [10] covers basic provisions for safeguarding from hazards arising out of conductors in electric supply substations, overhead and underground electric supply, and communication lines. It also covers work rules and safe clearances from live parts to ground and between phases. The Electrical Generating System Association [11] publishes performance standards for emergency, standby, and cogeneration equipment.

System protection is a fundamental requirement for all electrical systems. All switching devices must be applied safely within their interrupting ratings; faulted circuits must be isolated and relay protection should be properly designed and coordinated. Physical protection of equipment from tempering, damage, and environment must be provided. The operating personnel must be trained for the specific jobs. Essentially, all states in the US require that the system designs be performed under the seal of a licensed Professional Engineer, registered in that particular state.

In spite of this spate of standards, codes, and guidelines, the electrical power and distribution systems as designed and implemented currently may be inadequate with respect to personnel safety. Prevention through Design (PtD) is a new initiative sponsored by the NIOSH. This initiative was launched in a July 2007 workshop held in Washington, DC, to create a *national strategy* for PtD [12]. It may be defined as: "PtD involves addressing the occupational safety and health needs and redesign processes to prevent or minimize work-related hazards and risks associated with the construction; use; maintenance; and disposal of facilities, materials, and equipment."

This definition has a much wider base than merely the system designs of electrical installations. References [13–27] provide further reading.

1.10 Reliability Analyses

Reliability analyses are not covered in this series; however, some fundamental aspects are discussed in this chapter. Reliability is the probability of successful operation and is time dependent. For a system that has components with relatively constant failure rates, reliability is an exponentially decaying function with time; longer the time interval the longer is the reliability irrespective of system design. The reliability curve will be flatter for a well-designed system as compared to a poorly designed system.

System reliability assessment and evaluation methods are based upon probability theory that allows reliability of a proposed system to be assessed quantitatively. This is finding a wide application. Alternative system designs, redundancy, impact on cost of changes, service reliability, protection and switching, and system maintenance policy can be quantitatively studied. Using reliability evaluation methods, system reliability indexes can be computed. The two basic system reliability indexes *are the load interruption frequency and expected duration of load interruption events.* These can be used to compute other indexes, i.e., total expected average interruption time per year, system availability or unavailability at the load supply point, expected energy demanded, but unsupplied per year. Reliability also addresses emergency and standby power systems. Preventive maintenance has a large impact not only on the availability of systems but also on arc flash hazards—a poorly maintained system is more prone to failures including personal hazards.

If the time t over which a system must operate and the underlying distributions of failures of 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:

$$R(t) = \int_t^\infty f(t)\,dt \tag{1.38}$$

1.10.1 Availability

Availability can be defined as the percent of time a system is immediately ready for use, or an instant probability of a system being immediately ready for use. We speak of inherent availability (Ai) and operational availability (Ao). Ai consists of component failure rates and average repair time; Ao goes beyond Ai, in the sense, that maintenance downtime (Mdt), parts procurement time, logistics, etc. are included.

For Ai, we can write as follows:

$$\text{Ai} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \tag{1.39}$$

where,

MTBF: mean time between failures

MTTR: mean time to repair

Each probability distribution has unique PDF with notation $f(t)$. The area under that curve shows the relative probability of a failure occurring before time t, Figure 1.8a. Cumulative distribution function (CDF) can be calculated by the integral in the following equation:

$$F(t) = \int_0^t f(t)\,dt \tag{1.40}$$

where $F(t)$ is the probability occurring before time t. Plotting $F(t)$ gives CDF, Figure 1.8b. Finally, the reliability fuction $R(t)$ is the probability of a component not failing by time t:

$$R(t) = 1 - F(t) \tag{1.41}$$

The hazard rate or hazard function is defined for the remainder of the time:

$$H(t) = \frac{f(t)}{R(t)} \tag{1.42}$$

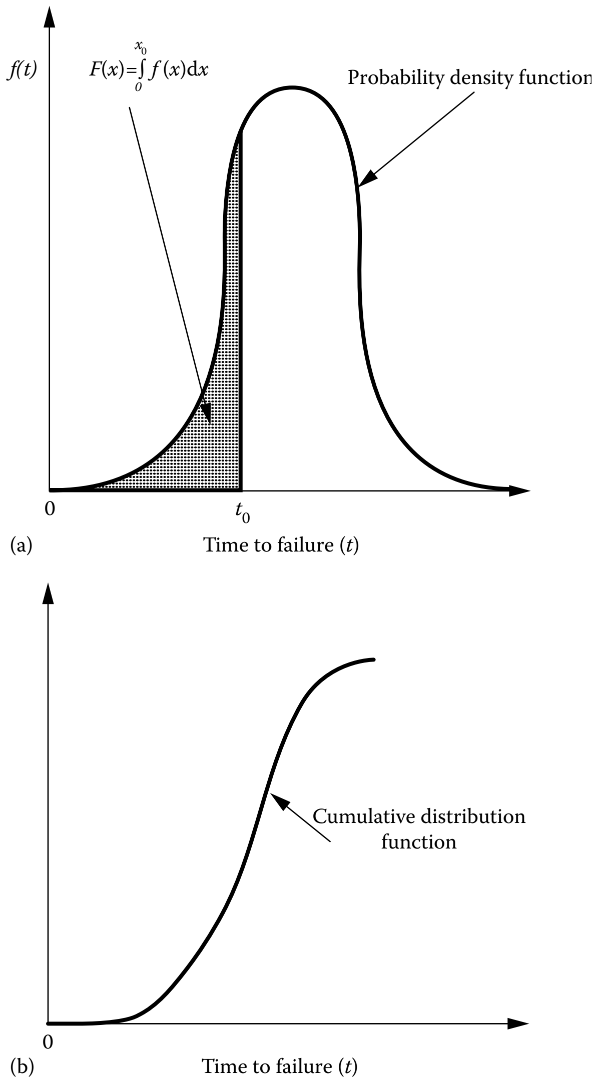

FIGURE 1.8
Probability of failure represented by the area under the curve of (a) PDF and (b) the cumulative distribution.

1.10.1.1 Exponential Distribution

The PDF for exponential distribution is given by the following:

$$f(t) = \lambda e^{-\lambda t} \tag{1.43}$$

The CDF is

$$f(t) = 1 - e^{-\lambda t} \tag{1.44}$$

And probability function is

$$R(t) = e^{-\lambda t} \tag{1.45}$$

The hazard function is therefore = λ.

1.10.2 Data for Reliability Evaluations

IEEE 493, Reference [28], contains the reliability data collected from equipment reliability surveys and a data collection program over a period of 35 years or more. Data needed for a reliability analysis will depend upon nature of the system being studied and the details of the study. Usually, data on individual system components and the time required to do various switching operations will be needed. System component data required are as follows:

1. Failure rates or forced outage rates associated with various modes of component failure
2. Expected average time to repair or replace a component
3. Scheduled maintenance outage rate of the component
4. Expected duration of a scheduled outage event

Switching the time data needed includes expected time to open and close a circuit breaker, disconnect or throw-over switch, replace a fuse link, and perform emergency operations such as installing jumpers.

The service reliability requirements of the loads and processes supplied are assessed to decide a proper definition of service interruption. It is not only the total collapse of voltage, but voltage sag or swell may also cause a shutdown. A *failure modes and effects* analysis is carried out. This means listing of all component outage events or combinations of component outages that result in an interruption of service at the load point being studied. Component outages are categorized as follows:

1. Forced outages and failures
2. Scheduled or maintenance outages
3. Overload outages

Component failure can be categorized by physical mode or type of failure.

1.10.3 Methods of Evaluation

- Cut-set method
- Network reduction
- Go algorithms
- State space
- Monte-Carlo simulations

The details of these analyses are beyond the scope of this series. In the cut-set method, computation of the quantitative reliability indexes can proceed once the minimal cut sets of the system have been found. The first step is to compute the frequency, expected duration and expected downtime of each minimal cut set. Statistical methods and expressions for frequency and expected duration of the most commonly considered interruption events associated with first-, second-, and third-order cut sets are then applied to assess overall reliability. Digital computers are used for the reliability analysis as the statistical manipulations become complex, even for small systems.

The minimum cut-set method is well suited for industrial power systems and commercial distribution systems. It lends itself to computer simulations and many commercial programs that are available. The procedure is

- Access the service reliability of equipment, loads, and processes.
- Perform a failure mode and effect analysis (FMEA), which amounts to listing of component outages or listing of component outages that result in interruption of services at the load point.
- Different types of modes and outage of components exist, which may be classified as follows:
  1. Forced outages or failures,
  2. Scheduled outages or maintenance outages,
  3. Overload outages.
- Compute the interruption frequency distribution, the expected interruption duration, and probability of each of the minimum cut sets.
- Combine the results to produce system reliability indexes.

The FMEA and determination of minimal cut sets is conducted by considering first the effect of outage of a single component and then the effect of overlapping outages of increasing number of components.

Define

f_s = interruption frequency = f_{csi}

r_s = expected interruption duration

$$r_s = \sum_{\text{min cut-set}} \frac{f_{csi} r_{csi}}{f_s} \quad (1.46)$$

$$f_s r_s = \text{total interruption time per time period.} \quad (1.47)$$

The first-, second-, and third-order cut sets are shown in Table 1.1

TABLE 1.1

Frequency and Expected Duration Expressions for Interruption Associated with Minimal Cut Sets

Forced Outages		
First-Order Minimal Cut Set	**Second-Order Minimal Cut Set**	**Third-Order Minimal Cut Set**
$f_{cs} = \lambda_i$	$f_{cs} = \lambda_i\lambda_j(r_i + r_j)$	$f_{cs} = \lambda_i\lambda_j\lambda_h(r_i + r_j + r_i r_{h+} r_j r_h)$
$r_{cs} = r_i$	$r_{cs} = \dfrac{r_j r_i}{r_i + r_j}$	$r_{cs} = \dfrac{r_j r_i r_h}{r_i + r_j + r_i r_h + r_j r_h}$

Forced outage overlapping schedule outage is given by the following expressions:

Second-order minimum cut set

$$r_{cs} = \left[\lambda_i' \lambda_j' \left[\frac{r_i' \, r_j'}{r_i' + r_j'} \right] + \frac{\lambda_j' \lambda_i' r_j' \left[\frac{r_j' \, r_i'}{r_j' + r_i'} \right]}{f_{cs}} \right] \tag{1.48}$$

Define

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

This standard provides a summary of all-industry failure rate and equipment outage duration data. Table 2.1 of this standard lists inherent availability and reliability data,

TABLE 1.2
Definition Summary for the Reliability Analysis

Parameter	Equation	Explanation of Symbols
Ai, inherent availability	MTBF/(MTBF + MTTR)	
Ao, operational availability	MTBM/(MTBM + MDT)	
Λ, failure rate (f/h)	T_f/T_p	T_f, total number of failures during a given T_p
MDT, mean down time	$(R_{dt} + R_{lt} + M_{dt})/T_{de}$	T_{de}, total downtime events, R_{dt}, total downtime for unscheduled maintenance, R_{lt}, total logistic time for unscheduled maintenance and M_{dt}, maintenance down time
MTBF, mean time between failure (h)	T_p/T_f	
MTBM, mean time between maintenance (h)	T_p/T_{de}	
MTTM, mean time to maintain (h)	M_{dt}/T_{ma}	T_{ma}, total number of scheduled maintenance in T_p
MTTR, mean time to repair (h)	R_{dt}/T_f	
$R(t)$ reliability	$e^{-\lambda t}$	

Note: Based on IEEE 493 [2].

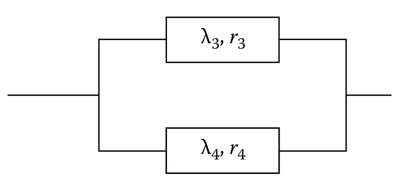

FIGURE 1.9
Two systems in parallel with different λ and r.

which is fundamental to the reliability analysis. Table 1.2 shows the definition summary from this standard.

When two repairable components are connected in parallel, as shown in Figure 1.9, the following expressions apply:

$$f_P = \frac{\lambda_3\lambda_4(r_3 + r_4)}{8760}$$

$$f_P r_P = \frac{\lambda_3 r_3 \lambda_4 r_4}{8760} \tag{1.49}$$

$$r_P = \frac{r_3 r_4}{r_3 + r_4}$$

Equations 1.49 are approximate and should be used when $\lambda_3 r_3/8760$ and $\lambda_4 r_4/8760$ are less than 0.01.

Table 1.3 shows the results of IEEE survey of reliability of electrical utility power supplies for industrial plants. This shows importance of utility supply source to which the distribution system is connected. Except for small distribution plants where the process interruptions can be tolerated without much loss of revenue, single source utility sources are not recommended. Consider that in a process plant with production rate of thousand of tonnes of product per day, a supply source interruption can amount to hourly loss of thousands of dollars. Then, there are processes where the loss of power can damage or jam the equipment and it takes days to clean up and restart the processes. For critical electronic equipment manufacture, like a power supply to Intel manufacturing facilities, the complete power supply is conditioned to be immune to voltage sags and swells, other power quality problems using solid-state devices that are discussed in Volume 2.

Table 1.4 shows failure modes of circuit breakers. Note that 42% of failures occur because of nuisance trips; the circuit breaker opens when it should not.

Example 1.2

Calculations of reliability of a simple radial system, shown in Figure 1.10 are from IEEE standard 493–2007. The results of calculations for the forced hour down time are shown in Table 1.5. The single utility power source and the single transformer are the greatest contributors to the failure rate. If a spare transformer is at hand or with cogeneration,

TABLE 1.3

IEEE Survey of Reliability of Utility Power Supplies to Industrial Plants

Number of Circuits, all Voltages	λ	r	λ_r
Single circuit	1.956	1.32	2.582
Double circuit Loss of both circuits[a]	0.312	0.52	0.1622
Double circuit-calculated value for loss of source 1 while source 2 is okay	1.644	0.15[b]	0.2466
Calculated two utility power sources at 13.8 kV that are assumed to be completely independent	0.00115[c]	0.66[c]	0.00076

[a] Data for double circuit that had all circuit breakers closed.
[b] Manual switchover time of 9 min to source 2.
[c] Calculated using single circuit utility power supply data and equations for parallel reliability.

TABLE 1.4

Failure Mode of Circuit Breakers–Percentage of Total Failure in Each Mode

Percentage of T_f (All Voltages)	Failure Characteristics
9	Backup protective equipment required, failed while opening
Other Circuit Breaker Failures	
7	Damaged while successfully opening
32	Failed 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

the λ_r is reduced. The results for some primary selective and secondary selective systems from this standard are shown in Table 1.6. Figure 1.11a through c applies to the primary selective systems and Figure 1.12 to the secondary selective system. It is seen that the primary selective systems (a) and (b) are almost identical with respect to λ_r, thus the additional cost of a 13.8 kV circuit breaker and cable connections can be avoided.

1.10.4 Reliability and Safety

A system designed for high MTBF is not necessarily the safest from the point of view of injuries and hazards to the worker. For example, an industrial distribution system served from a single source of power; one transformer connected to the utility source will not be very reliable. In such a system, any failure of a component connected in radial circuit can result in total failure of the served loads, i.e., failure of main transformer, circuit breaker, or interconnecting cables. This will call for more human intervention to attend to the failures. Yet, this simple radial system can be designed safe from arc flash hazard and worker safety considerations. A system with redundant parallel running transformers, alternate sources of power, standby generation and UPS systems, auto-transfer switches of power between sources will be more reliable with respect to reliability indices, but may not have the required worker safety features; for example, a proper interlocking of the sources may be missing or improperly designed. *It should not be construed that complex systems designed with higher reliability cannot be made equally or even safer than simpler systems.* For properly designed automated systems, lesser interruptions and human interventions will be needed. This will improve both—the reliability as well as the safety.

The maintenance aspects will be common for reliability and safety. Poorly maintained systems are neither safe nor reliable. The aspects of reliability and safety should converge for the effective system design.

To avoid man-machine interface (MMI) errors, the emphasis is upon *self-monitoring* and *self-correcting* systems with least amount of manual interference.

The IEC 61511 [24] has been developed as process sector implementation of the IEC 61508 [25]: "Functional Safety of Electrical/Electronic/Programmable Electronic Safety Related Systems." It has two basic concepts: The safety lifecycle and safety integrity levels (SILs). The safety lifecycle forms the central framework, and it is a good engineering procedure for safety instrumented systems (SIS) design in process industry (sensors, logic solvers,

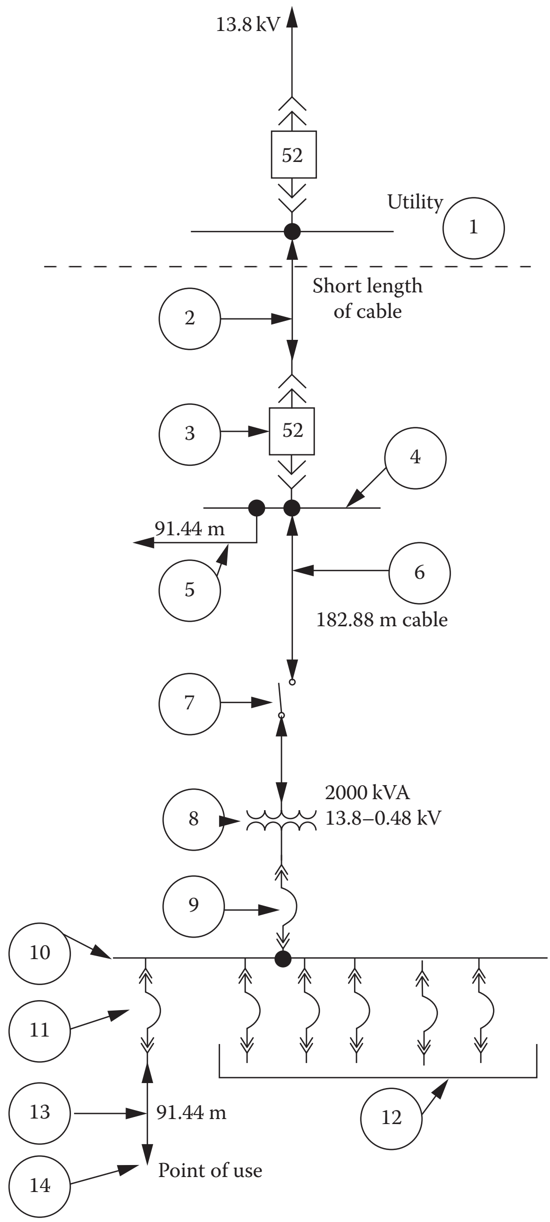

FIGURE 1.10
A radial distribution system, with one utility source for reliability evaluation using cut-set method.

and final elements are a part of SIS). In the safety lifecycle process, risks are evaluated and SIS performance requirements are established. Layers of protection are designed and analyzed. Then, an SIS is optimally designed to meet the particular process risk. SIL levels indicate order of magnitude of risk reduction. Table 1.7 shows safety integrity levels. SIL 1 has the lowest level of risk reduction and SIL 4 has the highest level of risk reduction. The standard suggests that applications that require the use of SIS of SIL4 are rare in the process industry; an exception can be nuclear plants. The standard mainly deals SIS and

TABLE 1.5

Reliability Analysis of Simple Radial System

Component Number	Component	λ	λ_r	Ai
1	13.8 kV utility power source	1.956000	2.582000	0.999705338
2	Primary protection and controls	0.000600	0.003000	0.999999658
3	13.8 kV metal clad 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)	0.002124	0.033347	0.999996193
6	Cable terminations	0.002960	0.002220	0.999999747
7	Disconnect switch	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	0.99999856
10	480 V switchgear bus	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	0.9999999957
13	Cable 480 V, 91.44 m (300 ft)	0.000021	0.000168	0.9999999981
14	Cable terminations (2) at 480 V	0.000740	0.000555	0.9999999937
	Total at 480 V point of use	1.990940	4.279332	0.999511730

Source: IEEE standard 493.
Note: The data for hours of downtime per failure are based upon repairing the failed unit.

TABLE 1.6

Reliability Comparison, Different System Configurations

	Switchover in Less Than 5 s		Switchover in 9 min			
Distribution System	λ	λ_r	λ	λ_r	λ	λ_r
Simple radial					1.990940	4.279332
Simple radial with a spare transformer					1.990940	3.367488
Simple radial with cogeneration					0.053069	1.741527
Primary selective to 13.8 kV utility supply	0.344490	1.855647	1.990940	2.102614		
Primary selective to load side of 13.8 kV circuit breaker	0.345938	1.867318	1.992388	2.114285		
Primary selective to primary of the transformer	0.333566	1.665287	1.992018	1.914055		
Secondary selective	0.322499	0.233556	1.990883	0.483814		

interface between SIS and other safety systems in requiring that a process hazard and risk assessment be carried out.

The difference between SIL related to *a single piece of equipment* and *a set of processes* must be clearly distinguished. In the USA, the onus of specifying a particular equipment meeting the required safety levels (i.e., OSHA, UL, ANSI/IEEE standard requirements) lies

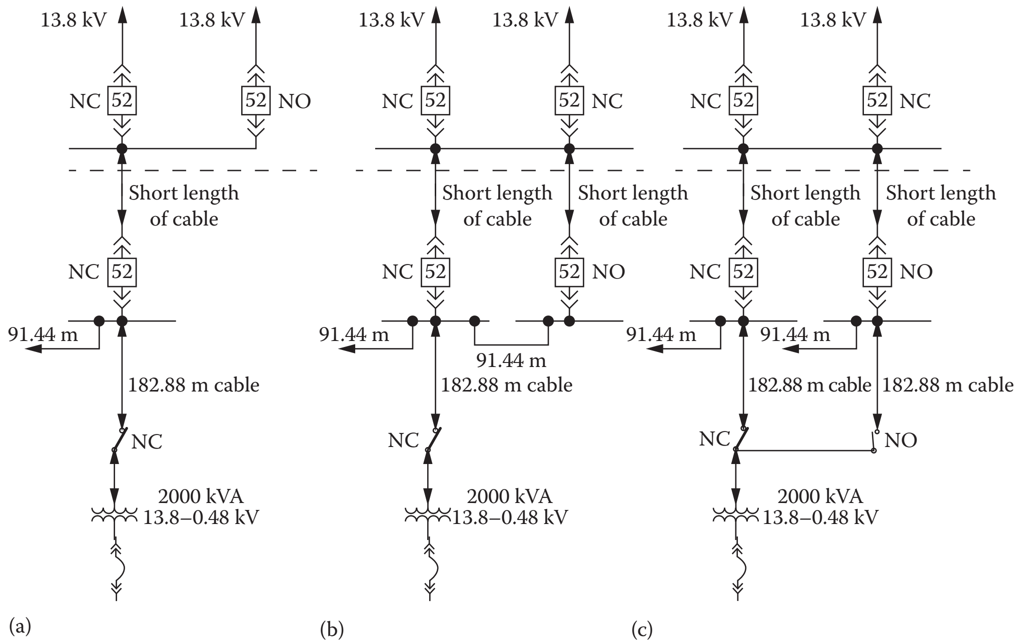

FIGURE 1.11
The system with duplicate utility sources: (a) primary selective; (b) primary selective system to the load side of the 13.8 kV circuit breaker; and (c) primary selective system to the primary of the transformer.

with the user. In Europe, the machine manufacturers must meet the specified SIL level. Relevant references are Standards: IEC 62061 also ISO 13849-1, [26,27].

IEC 61511 Part 3 details the guidelines for selecting SIL in hazards and risk analysis. The information is intended to provide a broad range of global methods used to do such analysis. There are several informative annexes, of which Annex A covers As Low As Reasonably Practical (ALARP) principle and tolerable risk concepts, Figure 1.13.

1.11 Extent of System Modeling

The system to be studied is a small part of an overall grid system, Figure 1.14. It is important that the impact of the larger system should be carefully accounted for the accuracy of the type of study being considered. This requires that the boundary conditions should be clearly established. Consider a large system consisting of many generators, transmission lines, transformers, and cables. According to Thévenin theorem, any node of interest can be pulled out from a larger system and the system impact modeled by equivalent Thévenin impedance in series with an equivalent voltage source at the point of interconnection. It is, however, obvious that this equivalent Thévenin impedance cannot be a fixed number and will vary with the changes in the operation of the system; for example, some of the generators may be off-line and transmission lines may be out of service.

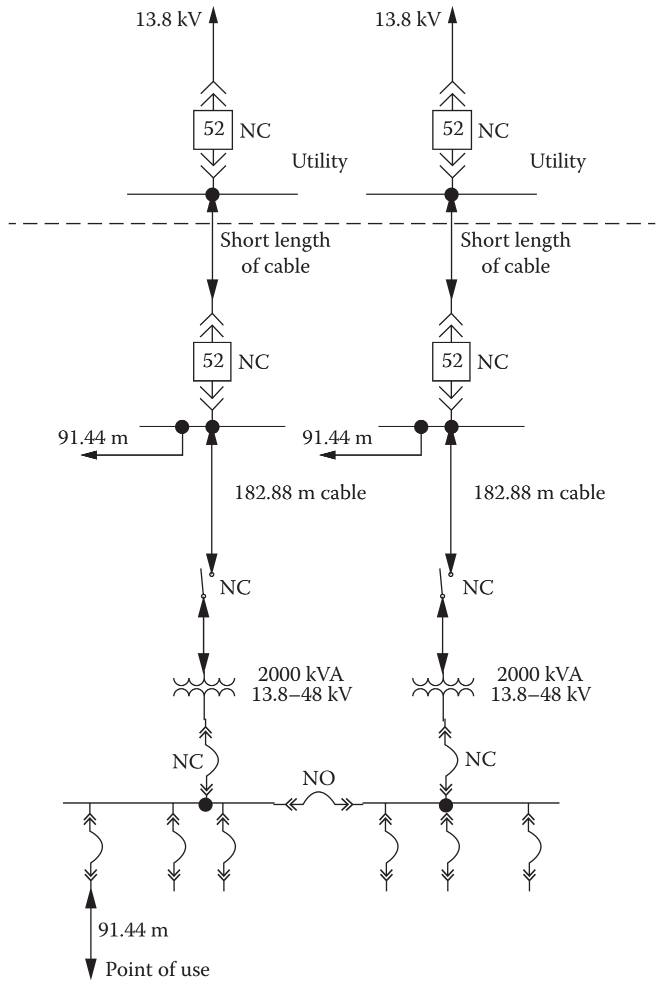

FIGURE 1.12
A secondary selective system.

1.11.1 Short-Circuit Calculations

For the short-circuit conditions, the equivalence is established at the point of interconnection with one single number *representing the short-circuit levels in symmetrical kA.*

Three-phase short level in symmetrical kA and its X/R ratio, maximum and minimum values

Single line to ground fault in symmetrical kA and its X/R ratio, maximum and minimum values

Based on this data, the maximum and minimum values of positive, negative, and zero sequence impedances can be calculated for the short-circuit study.

According to IEEE standards for the short-circuit calculations, this utility source can be represented by an *invariant impedance*. Care has to be exercised in making this assumption. Consider that a large generating station is in the vicinity of the

TABLE 1.7
SIL for Safety Functions Operating on Demand or in a Continuous Demand Mode

Safety Integrity Level	Demand Mode of Operation (Average Probability of Failure to Perform Its Design Function on Demand-Pdf)	Continuous/High Demand Mode of Operation (Probability of a Dangerous Failure per Hour)
4	$\geq 10^{-5}$ to $<10^{-4}$	$\geq 10^{-9}$ to 10^{-8}
3	$\geq 10^{-4}$ to 10^{-3}	$\geq 10^{-8}$ to 10^{-7}
2	$\geq 10^{-3}$ to 10^{-2}	$\geq 10^{-7}$ to 10^{-6}
1	$\geq 10^{-2}$ to 10^{-1}	$\geq 10^{-6}$ to 10^{-5}

Source: IEC 61508-1, Tables 2 and 3.

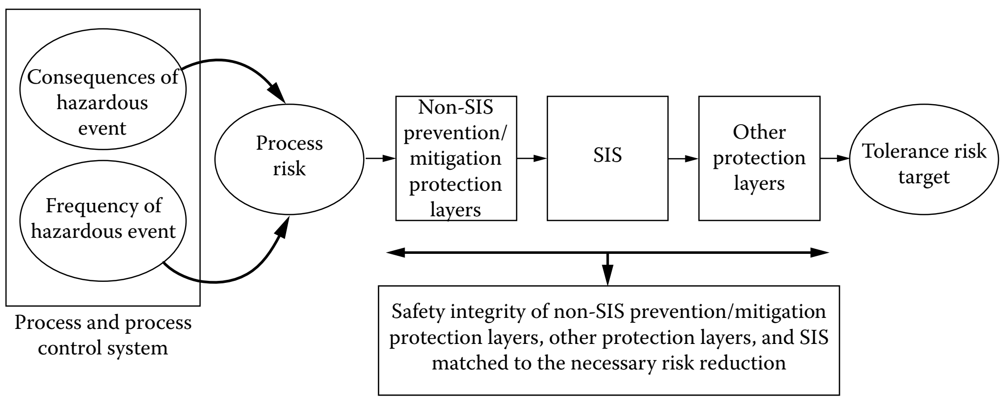

FIGURE 1.13
Risk and safety integrated systems, see text.

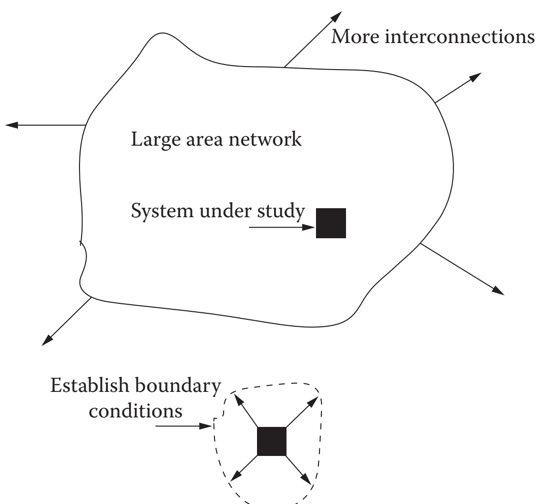

FIGURE 1.14
The extent of system modeling for power system studies.

industrial plant for which the studies are to be undertaken. It will be erroneous to represent the source impedance with an invariant single number representative of symmetrical and asymmetrical fault current situation—this will give erroneous results with respect to momentary or first cycle short-circuit calculations. It will be necessary to extend the boundary of modeling to include the generating station, and its interconnections.

1.11.2 Load Flow Calculations

The concept of the swing bus is defined in Volume 2. It may be considered an ideal Thévenin source as well an ideal Norton equivalent. Any amount of current taken from this source will not alter the voltage a bit. A stiff utility source may approximate it and may be represented as swing bus, but there are lots of electrical distribution systems connected to weak utility sources. On a load flow, declaring the utility source as a swing bus will give erroneous results as it will ignore the voltage dip occurring in the impedance of the utility source, which is not zero. A fictitious impedance representative of the source can be calculated and provided in series with a large stiff source, see Volume 2.

1.11.3 Harmonic Analysis

In power system harmonic analysis, inadequate representation of the boundary limits may give rise to totally invalid results, see Volume 3 for further discussions.

1.12 Power System Studies

Power system analysis is a vast subject. Consider the following broad categories:

- Short-circuit studies, in AC and DC systems Volume 1
- Load flow studies, Volume 2
- Stability studies; large rotor angle, small disturbances, and voltage instability—a brief introduction is provided in Volume 4
- Motor starting studies, Volume 2
- Optimal load flow, contingency, and security analysis studies, Volume 2
- Harmonic analysis studies, harmonic mitigation, flicker mitigation, and harmonic filter designs studies, Volume 3
- Application of FACTS and power electronics studies, Volume 2
- Transmission and distribution lines planning and design studies, underground transmission, and distribution studies
- Insulation coordination and application of surge protection studies
- Switching transient and transient analysis studies
- Power system reliability studies
- Cable ampacity calculation studies in UG duct banks, submarine cables, oil filled cables, and the like

- Torsional dynamics studies
- HVDC transmission studies, short-circuits, and load flow in DC systems studies—a brief description is provided in Volumes 1 and 2
- Renewable generation interconnections with utility grid—brief description is included in Chapter 3
- Wind power and renewable energy sources, feasibility studies, and their integration in the grid studies
- Power quality for sensitive and electronic equipment studies
- Ground mat (grid) design for safety studies, system grounding studies, grounding for electronic equipment studies
- Protective relaying and relay coordination studies, Volume 4
- Arc flash hazard analysis studies—a brief description is provided in Volume 4
- Energy conservation studies
- Studies for design and applications of standby power systems

In addition, specific studies may be required for a specific task, for example, transmission line designs or generating stations, transmission substations, and consumer load substations.

In power system studies, there is some data that are transparent between the various types of studies. For example, correct impedance data model is required for short-circuit, load flow, and harmonic analyses. The load flow algorithms are modified for harmonic penetration and harmonic power flow, see Volume 3. Also short-circuit calculations are a prior requirement for harmonic analyses. For the protective relaying studies, a prior knowledge of symmetrical and unsymmetrical fault current calculations and symmetrical components is required. *The repetitions from one volume to another are avoided without loss of continuity. A reader may not be interested in all aspects of the power system studies, and this limitation should be noted. Appropriate references are provided as required.*

1.13 Power System Studies Software

Around 25 years back, there was no power system studies software for PC use. Today, the market is flooded with many options available for the choice of softwares for a particular study. However, all the software programs available may not have the same or identical capabilities. This puts an onerous of selection of the right software not only for the current system to be studied but also for the future studies. Further, every vendor claims that the software meets IEEE and IEC requirements. However, there is no independent body to verify this claim and some variations are noted in the end results for the same system configuration. No specifications have been written to verify the claims of the vendors. There are no standards established on the input data and output formats.

The databases vary in their capabilities. User-defined models are possible in some cases. The databases are, generally, not transparent between various softwares. This means that if a different software is to be used, other than that on which the system was modeled, all data will need to be reentered, which can be very time consuming.

The desirable capabilities of softwares are discussed in appropriate sections in this series.

1.14 System of Units

The SI units are based on meter-kilogram-second-ampere (mksa) system. These have been adopted by standardization bodies of the world, including IEC, ANSI, and IEEE. The USA is the only industrialized nation in the world that does not mandate the use of SI units. Even in many IEEE technical papers in conferences and IEEE Transactions, SI units are not strictly followed, though IEEE insists that SI units are used. The engineering work in the USA still holds foot-pound-second (FPS) system. The US congress has the constitutional right to establish measuring units; and has not enforced any system. The metric system (now SI) was legalized in 1866, and is the only legal measuring system, but other non-SI units are legal as well.

Other countries adopted SI units in 1960–1970. Some denounced as branding it "un-American." Progressive businesses and educational institutes asked Congress to mandate it. As a result, in 1988 Omnibus Trade and Competitiveness Act, Congress established SI as the *preferred* system for the US trade and commerce and urged all federal agencies to adopt it by 1992 or as early as possible. SI remains voluntary for the private US businesses.

This series uses both the units, SI and FPS units.

Problems

1.1 Figure P1.1 shows a parallel RLC circuit A differential equation for the total current drawn by the circuit that can be written as follows:

$$i(t) = \frac{e_C}{R} + C\frac{\mathrm{d}e_C}{\mathrm{d}t} + \frac{1}{L}\int_{-\infty}^{t} e_C(t)\,\mathrm{d}t$$

Write equations for the state model.

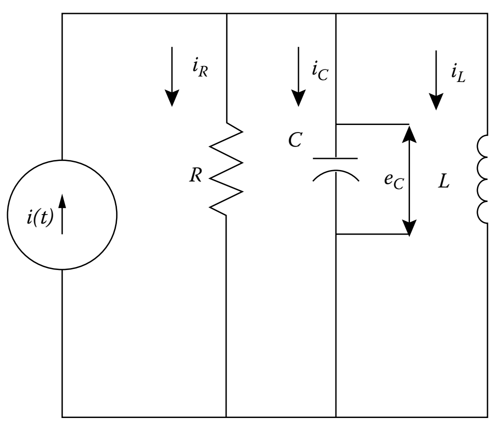

FIGURE P1.1
A parallel RLC circuit excited by a current source.

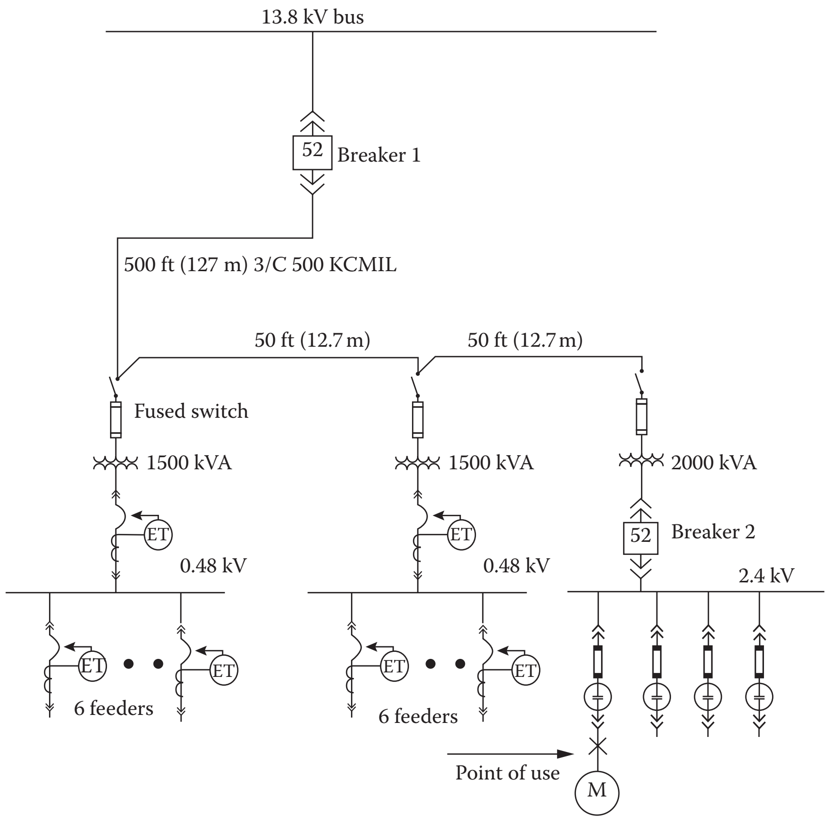

FIGURE P1.2
A simple distribution system for calculation of reliability indices.

1.2 Consider the following expressions:

$$y(t) = ax(0) + br(t)$$

$$y(t) = [r(t)]^2$$

Do they represent a linear or nonlinear systems?

1.3 Calculate reliability indices similar to Table 1.5 for the configuration shown in Figure P1.2 at the point of use.

1.4 Consider that two systems continuously operate in parallel and have the following parameters, pertaining to each subsystem:

$$\lambda_1 = 1.3, \lambda_2 = 1.5$$

$$r_1 = 0.67, r_2 = 0.34$$

Calculate overall λ_r

1.5 Describe different maintenance strategies for electrical power systems (not discussed in the text)

References

1. www.ieee.xplore, Digital Library 2017.
2. IEEE color books

    141: IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book), 1993.

    142: IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book), 1991.

    241: IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (IEEE Gray Book), 1997.

    242: IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book), 2001.

    399: IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (IEEE Brown Book), 1997.

    446: IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (IEEE Orange Book), 2000.

    493: IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (IEEE Gold Book), 2007.

    602: IEEE Recommended Practice for Electric Systems in Health Care Facilities (IEEE White Book), 1996.

    739: IEEE Recommended Practice for Energy Management in Commercial and Industrial Facilities (IEEE Bronze Book), 1995.

    902: IEEE Guide for Maintenance, Operation and Safety of Industrial and Commercial Power Systems (IEEE Yellow Book), 1998.

    1015: IEEE Recommended Practice for Applying Low-Voltage Circuit Breakers Used in Industrial and Commercial Power Systems (IEEE Blue Book).

    1100: IEEE Recommended Practice for Powering and Grounding Electronic Equipment (IEEE Emerald Book), 1999.

    551: Recommended Practice for Calculating Short-Circuit Currents in Industrial and Commercial Power Systems (IEEE Violet Book), 2006.
3. National Electrical Code (NEC) NFPA-70-2014.
4. NFPA Publications:
    a. HFPE and Society of Fire Protection Engineers, SFPE Handbook of Fire Protection Engineering.
    b. 101H, Life Safety Code Handbook.
    c. 20. Centrifugal Fire Pumps.
    d. 70B. Electrical Equipment Maintenance.
    e. 70E. Electrical Safety Requirements for Employee Workplaces, 2015.
    f. 72. National Fire Alarm Code.
    g. 75. Protection of Electronic Computer/Data Processing Equipment.
    h. 77. Static Electricity.
    i. 78. Lightning Protection Code.
    j. 79. Electrical Standards for Industrial Machinery.
    k. 92A. Smoke Control Systems.
    l. 99. Health Care Facilities.
    m. 110. Emergency and Standby Power Systems.
    n. 130. Fixed Guide-Way Transit System.
5. Federal Register. Superintendent of Documents, U.S. Government Printing Office, Washington DC 2040.
6. NIOSH. Publications Dissemination, 4676 Columbia Parkway, Cincinnati, OH 45226.
7. TEC. 1111, 19th Street, Washington DC 20036.

8. NEMA 2101 L Street, NW, Suite 300, Washington DC 20037.
9. Popular Handbooks.
   DG Fink, HW Beaty. *Standard Handbook for Electrical Engineers*, 15th Edition, McGraw-Hill, New York.
   T Croft, CC Carr, JH Watt. *American Electricians Handbook*, 12th Edition, McGraw-Hill, New York.
   JG Webster, Ed. *Wiley Encyclopedia of Electrical and Electronics Engineering*, 21 Volumes, John Wiley & Sons, New York, 1999.
   Illuminating Engineering Society (IES) Handbook, Vols. 1 and 2. 1221, Avenue of the Americas, New York, 10020.
   Electrical Transmission and Distribution Reference Book, 4th Edition, East Pittsburg, PA, Westinghouse Electric Corporation, 1964. *Applied Protective Relaying*, Westinghouse Electric Corporation, Coral Springs, Florida, 1982.
   RS Smeaton, Ed. *Motor Applications and Maintenance Handbook*, McGraw-Hill, New York, 1987.
   DL Beeman. *Industrial Power Systems Handbook*, McGraw-Hill, New York, 1955.
   Edison Electrical Institute. *Underground Systems Handbook*, 1957.
   RS Smeaton, Ed. *Switchgear and Control Handbook*, McGraw-Hill, 1987.
   JM McPartland. *Handbook of Practical Electrical Design*, McGraw-Hill, New York, 1984.
10. NESC, C-2, National Electrical Safety Code, C-2.
11. EGSA. P.O. Box 9257, Corel Springs, FL 33065.
12. E Manuele. Prevention through design: Addressing occupational risks in the design and redesign processes, In special issue of By Design, Engineering Practice Specialty of American Society of Safety Engineers, pp. 1–13, October 2007.
13. ANSI Z10, Occupational Safety and Health Management Systems, 2004.
14. HL Floyd. The NIOSH prevention through design initiative, in *Conf. record IEEE IAS Petroleum and Chemical Industry Committee Tech. Conference*, pp. 363–369, September 1999.
15. JC Cawley, GT Homce. Trends in the electrical injuries in the U.S. 1992–2002, *IEEE Trans Ind Appl Mag*, 44(4), 962–972, 2008.
16. JA Gambatese, J Hinze, M Behm, Investigations of the viability of designing for safety, The Center to Protect Workers' Rights, Silver Spring, MD, Tech. Rep., May 2005.
17. Council; Directive 92/57/EEC. The implementation of minimum safety and health requirements at temporary or mobile construction sites, European Union Regulation, Official Journal L245, pp. 6–22, June 1992.
18. Construction Design and Management Regulations, UK Health and Safety Executive, Statutory Instrument No. 320, pp. 1–9, 2007.
19. Commonwealth of Australia, National OHS Strategy 2002–2012, Tech. Rep., pp. 1–9, 2002.
20. S Jamil, A Golding, HL Floyd, M Capelli-Schellpfeffer, Human factors in electrical safety, in Proc. *IEEE IAS Petroleum and Chemical Industry Tech. Conf.* pp. 349–356, September 2007.
21. WC Christensen, Safety through design: Helping design engineers: 10 key questions, American Society of Safety Engineers Prof Saf pp. 32–39, March 2003.
22. ASSE: TR-Z790.001, Prevention through design guidelines for addressing occupational risks in design and redesign processes, American Society of Safety Engineers, Tech. Rep., pp. 1–28, October 2009.
23. NETA. International Electric Testing Association. MTS1993. Maintenance Testing Specifications.
24. IEC 61511-SER Ed. 1.0, Functional Safety-Safety Instrumentation Systems for Process Industry Sector—All Parts, 2004.
25. IEC 61508, Ed. 2.0 Functional Safety of Electrical/Electronic/Programmable Electronic Safety—Related Systems—All Parts, 2010.
26. IEC 62061-1, Ed. 1.0. Guidance for Application of ISO 13849-1 and IEC 62601 in the Design of Safety Related Control Systems for Machinery, 2010.
27. IEC 62061. Safety of Machinery—Functional Safety of Safety in Related Electrical Electronic and Programmable Electronic Control Systems, 2005.
28. IEEE Standard 493. Design of Reliable Industrial and Commercial Power Systems.