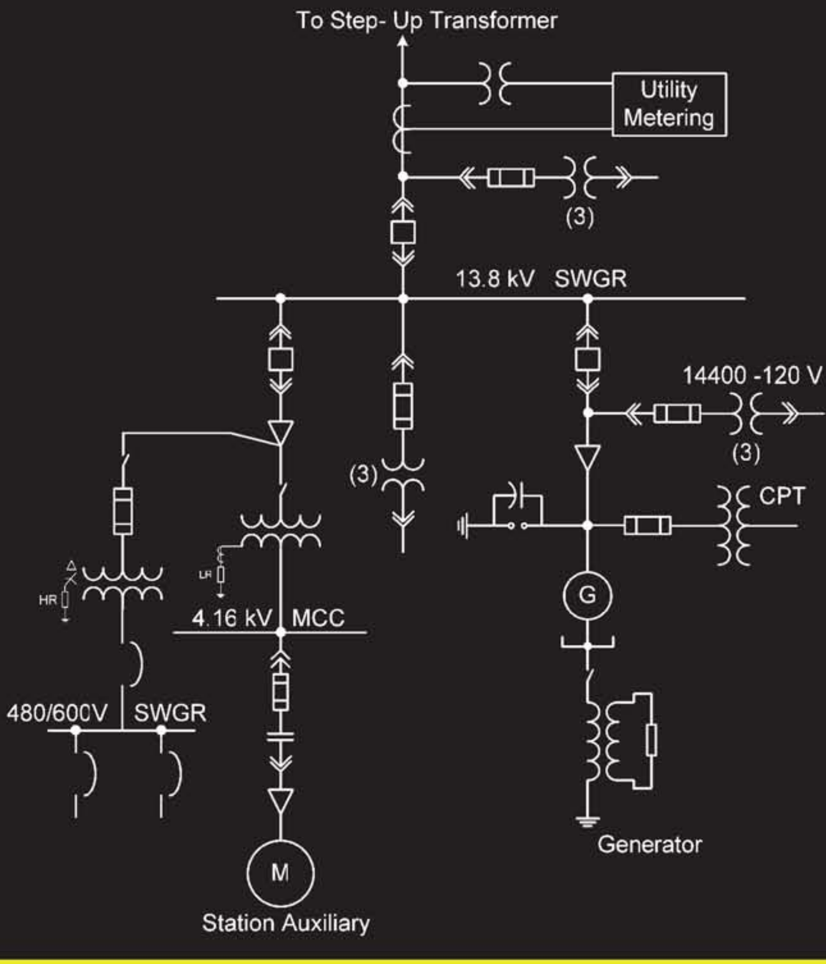
# INDUSTRIAL POWER SYSTEMS

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CRC Press
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# *Dedication*

My father dedicated the draft version of this book to my mother, his wife Shamim, whose love, patience and support inspired him to pursue knowledge and share it with others.

The publication of this book was my father's dream, as it will allow the knowledge he acquired over the years to be shared with others on a larger scale. I'm grateful for having had the opportunity to play a small role in making his dream come true. I would like to dedicate the final version to him.

*Sheeba Khan*

# Contents

# Acknowledgments

This book was inspired by power systems courses developed and taught by my father for IEEE Continuing Education (Montreal) over several years. It was intended to respond to what he felt was a need in the field for an engineering/design guide for all working engineers, particularly younger ones who are not exposed to power systems during their undergraduate studies and who may not get guidance or training at their work place. It was an idea which was enthusiastically supported and encouraged by members of IEEE Continuing Education (Montreal), the not-for-profit engineering education organization my father collaborated with for over thirty years.

When he passed away unexpectedly, the book was incomplete. IEEE members approached me and asked that I continue where my father had left off. I was apprehensive about taking on such a project without an engineering background, but IEEE was insistent that it was needed, and offered to assist in its completion. I knew my father had been very committed to the project, and finally, upon reflection, I decided to take it on, despite my concerns. Fortunately, my father's former colleagues, as well as members of IEEE came to my aid whenever requested, and provided the guidance and assistance needed to complete my father's book. Michael Care, Gabor Furst, and Vijay Sood provided much-needed expertise and help in editing, and Maurice Huneault also assisted. Finally, this project might not have been completed if not for the dedication of Ahmed Ghariani, my father's former assistant and mentee, who worked tirelessly to compile materials, draw diagrams and provide constant assistance whenever needed. This book would not have been possible without the contributions and dedication of these dear friends and colleagues.

**Sheeba Khan**

# SHOAIB A. KHAN

May 4, 1936 - February 10, 2005

Shoaib Khan was an electrical engineer who worked for over 40 years in power systems engineering, application, and protective relaying for power (hydro, thermal, nuclear), pulp and paper, mining and metals, and chemical plants in North America and overseas. Born in India, he received a bachelor of science degree in electrical engineering with major in electric power from Banares Hindu University in 1957. He worked with Kaiser Engineers and M.N. Dastur & Co in India until 1965, when he immigrated to Canada with his wife and young daughter. In Canada, he was responsible for the engineering, construction and operation of steel, aluminium and power plants. He soon became known as an expert in power systems and protection, and organized, developed and taught courses in those areas. He wrote numerous technical papers on power systems, application engineering and protection, some of which have been published in IAS/PES transactions and *Pulp & Paper Canada*.

Shoaib was a senior member of the Institute of Electrical and Electronic Engineers (IEEE), and was very active with the IEEE Education Committee (Montreal Section) for over thirty years. He received the IEEE Centennial and Third Millennium Medals for achievement in education, the Honoured Engineers Medal and the Meritorious Engineering Award from the IEEE Pulp and Paper Industry Committee in 2001. He was also an auxiliary professor with the Department of Electrical Engineering and a guest lecturer with the Department of Chemical Engineering at McGill University, Montreal, where he organized, developed, and taught courses in power systems and protection.

Shoaib will be remembered by all his colleagues and friends for his dedication to the advancement of applied engineering, and for his hard work and dedication to education in his field of endeavor. He was not only an outstanding engineer, but also a true friend to his colleagues and a committed educator and supporter of young engineers.

# 1 Introduction

Based on the author's 40 years of hands-on experience in many industries, *Industrial Power Systems* provides the practicing engineer with modern, wide-ranging, and practical information, from the planning and design of electrical supply to electrical installations for industrial power systems. Using materials from IEEE courses developed for practicing engineers (under the banner of the IEEE Montreal Section), this comprehensive book provides a wealth of practical experience in a readable tone.

The book illustrates the importance of power systems, which is sometimes overlooked in practice. A power system is very much like a culture, varying from one type of industry to another in the same manner as traditions vary from one ethnic group to another. Each industry tries to maintain its own traditional practices which were evolved just after World War II. Those practices were influenced by economic constraints, process needs, technology available at that time, and fast growth. Some industries still try to maintain the same traditions when it comes to their power system but keep modernizing in the areas of controls and communications.

The main reason for the present situation is a lack of awareness for a reliable system on the part of power engineers and senior managers. The power system is still treated as a service only and not considered as an essential element to maintain product quality and continuity of operations. Also, the plant power distribution system generally represents a relatively small portion of the entire plant cost (5% to 10%), yet the production and output of the other 90% to 95% of plant investment is dependent on the service delivered by that investment in the power distribution system. The investment will return a profit only if electric power is continuously available in the quantities and of the quality desired.

This book covers the salient engineering features and design procedures, including power system studies, grounding, instrument transformers, medium-voltage meters, and many more topics. Chapters are easy to use and sufficiently detailed to address plant design engineering problems. An exhaustive list of standards and technical papers is also provided for further study.

Long overdue, *Industrial Power Systems* is a must-have for anyone involved in power engineering, including students, instructors, engineers, and senior management involved in the design and maintenance of power distribution systems.

# 2 System Planning

## 2.1 INTRODUCTION

The power system plays an important role in a process plant. The plant operations and production depend on a safe and reliable power system. Each plant power system design, whether new or an expansion to an existing system, must be analyzed to ensure that it is safe, reliable, meets the present objective, and permits expansion for future needs. This chapter outlines the system planning considerations and provides guidelines. References [S1] and [S2] provide guidelines for planning and designing a reliable power system.

## 2.2 BASIC DESIGN CONSIDERATIONS

The industrial power system planning and design must include the following considerations at the initial and planning or design stage.

### 2.2.1 Safety of Life

Human life is of utmost importance, and safety shall never be compromised. Electrical codes prescribe minimum installation practices, such as working space, clearance from live parts, minimum protection against overcurrent, etc. Major applicable electrical codes for North America are: National Electrical Code (NEC) [S17], Canadian Electrical Code (CEC) [S18], National Electrical Safety Code, etc. Sometimes states, provinces, or municipalities institute local codes in addition to NEC and CSA. Insurance underwriters such as Factory Mutual institute their standards and guidelines, which are over and above the relevant electrical codes and standards.

Electrical equipment minimum quality standards are prescribed in the standards and guides of the Institute of Electrical and Electronics Engineers (IEEE), the National Electrical Manufacturer's Association (NEMA), Underwriters Laboratories (UL), and the International Electrotechnical Commission (IEC). UL maintains a continuing service in testing and certifying the products of electrical manufacturers, principally those to be used for industrial and commercial applications.

The system planning and design shall include the following to ensure the safety of personnel and preservation of plant property:

- Equipment and installation shall conform to relevant codes and standards.
- Provide adequate working space and safe clearances around the electrical equipment, dead-front equipment for low- and medium-voltage systems, insulated bus and connections for metal-enclosed equipment, and adequate system and equipment grounding.

- Design the system to permit maintenance of equipment and circuits in a de-energized state without plant shutdown.
- Provide fully rated and protected equipment to withstand maximum short-circuit and load currents.
- Provide personnel protective equipment (PPE) such as insulated gloves, fire-retardant or fireproof clothing, and warning signs.
- Provide operations and maintenance instructions, such as built-in wiring and interlocking diagrams.
- Install emergency lighting for the safety and safe exit of personnel during power outage.

### 2.2.2 Reliability of Utility Power Supply

Ensure that the quantity, quality, and reliability of the utility power supply meets the plant power requirements. A dedicated line is more reliable and is subject to fewer power interruptions than a shared line. Distribution lines may have interruption rates of about 12 times per 100 km when compared with a 120 kV transmission line of the same length. Hence power supply at transmission voltage such as 120 kV or 230 kV is recommended.

Utility power systems, including transmission and distribution lines, are subject to disturbances such as lightning strokes and ground faults that cause voltage sags. These voltage sags may cause the undervoltage and control devices to trip and motors to stall, resulting in plant shutdown.

### 2.2.3 Reliability of Plant Distribution System

Plant power distribution system design must be considered during the planning and conceptual design stage. The IEEE Gold Book [S8] provides guidelines for the design of a reliable power system as well as surveys carried out on the failure of equipment and systems. The key steps to increase the reliability of the plant power system are:

- Select modern, standard, and reliable equipment. Apply good installation and preventive maintenance practice.
- Use a minimum of two circuits or feeds, each from a different bus, to major and critical load centers. Do not run both circuits in the same cable tray or duct bank.
- Do not use bare conductor overhead lines within the plant boundary. Run the distribution feeders above ground wherever possible; the failure rate of a directly buried cable is considerably higher.
- System neutral grounding reduces transient overvoltage on single line-to-ground faults, thus minimizing insulation failures.
- A coordinated short-circuit and overcurrent protection isolates the faulted circuit, protects the equipment, confines the power outage to the protected zone, makes it easier to locate the fault, and prevents fires.

### 2.2.4 Simplicity of Operation and Maintenance

The majority of faults in utility distribution networks are caused by environmental reasons, such as a tree branch falling on the bare conductor overhead line, lighting strikes, etc. For this reason, the distribution networks are interconnected to facilitate alternative power supply routes. However, the majority of the faults in industrial systems are caused by insulation failure and sometimes by inadvertent or accidental contacts. The design of an industrial power distribution system shall be simple, utilizing radial feeds. This approach simplifies the interlocking and the maintenance, thus increasing safety.

### 2.2.5 Voltage Regulation and Flicker

This subject is covered in section 2.6.

### 2.2.6 Cost (Last Priority)

The cost of an electric power system is small compared with the total cost. Safety, reliability, voltage regulation, maintenance, and provision for future expansion shall be given priority.

## 2.3 PLANT DISTRIBUTION SYSTEMS

### 2.3.1 An Overview

A typical process plant distribution system in a single (one)-line diagram form is shown in fig. 2.1. This is composed of a main substation, primary distribution, secondary distribution, and in-plant generation. Electric utility companies supply power at high voltages (HV) via transmission lines or sometimes insulated power cable. HV power is stepped down to medium voltage for primary distribution to different plant facilities or load centers.

Each industry has implemented some specific and unique features in its plant electrical systems that have evolved with time and are based on experience. System planners and designers are advised to study a few typical plant distribution systems of similar installations before developing their own. IEEE guides are an excellent help for everyone involved with this task.

### 2.3.2 Plant Main Substation

High-voltage power from the utility is stepped down in the plant main substation for the primary distribution system. The electrical and nonelectrical items include:

- *Nonelectrical*: Gantry for terminating incoming and outgoing transmission lines, support structures, equipment foundation, perimeter fence, control building, grounding, underground oil containment, etc.
- *Electrical items*: Power transformers, circuit breakers, disconnect switches, instrument transformers, reactors, capacitors, power and control cable, protection and control, communications, lighting, heating, etc.

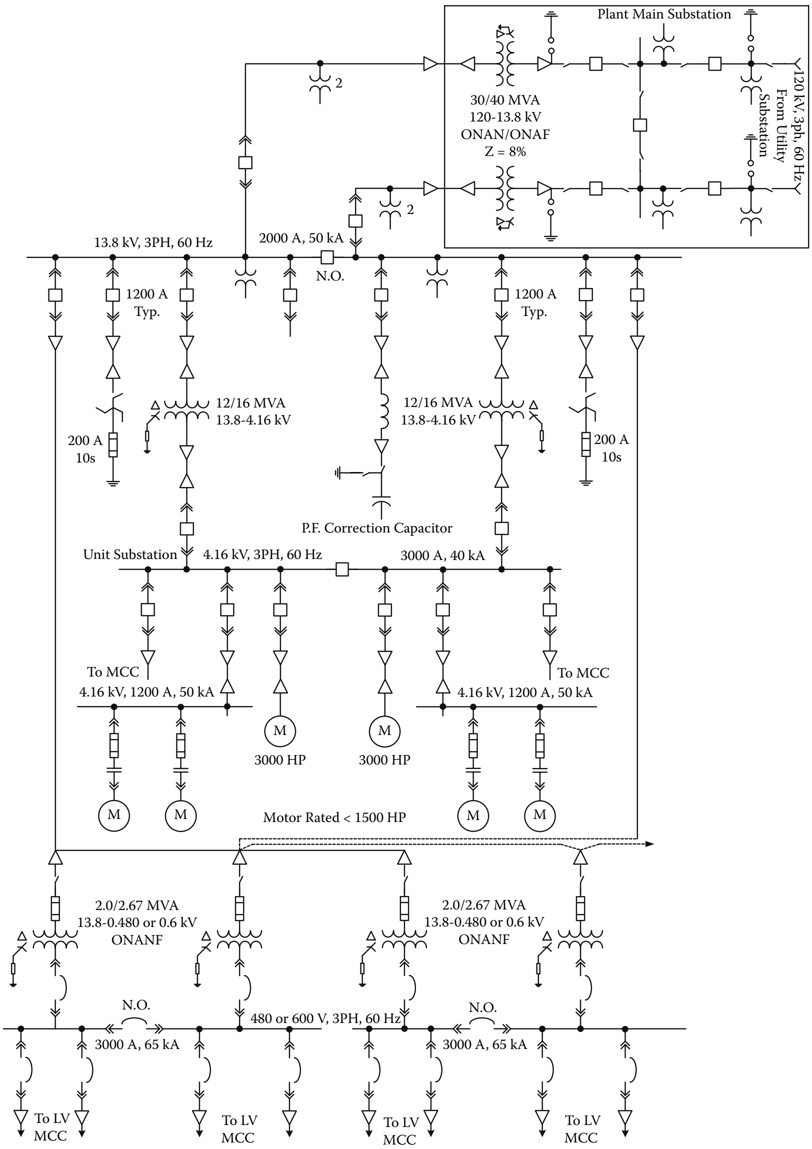


**FIGURE 2.1** Typical one-line (single line) diagram

### 2.3.3 Primary Distribution System

This includes distribution from the plant main substation or generating station to the primary load centers or switchgear located in different plant facilities. A radial system with two feeders to each area is used for greater reliability. The following voltage levels can be considered as a guide:

- 4.16 kV for small and medium-sized plants (load up to 15 MVA)

- 13.8 kV for medium and large plants (load exceeding 20 MVA)
- 34.5 kV for large plants where individual facilities are remote from each other

### 2.3.4 Secondary Distribution System

This includes distribution from the primary load centers to secondary load centers, unit substations, low-voltage switchgear, and utilization equipment such as motor control centers, motors, heating, and lighting. For greater reliability, a secondary selective arrangement is recommended for the load centers.

### 2.3.5 In-Plant Generation

In-plant generation is used when one of the following conditions is present:

- Steam is available at a suitable pressure and temperature. (It is economical to build a power plant using electric generators driven by steam turbines.)
- Power is not available from a utility company.
- Purchased power from the utility company is unreliable or the cost is very high.

### 2.3.6 Emergency Power Supply

Emergency power is required where an outage of normal source will be detrimental to process and equipment. This may include motors, valves, emergency lighting, controls, etc. Electric generators driven by diesel engines are used. The unit is started automatically after about a 20-s delay upon loss of power. The diesel generator is started periodically to ensure that it is in a proper operating condition.

The diesel engine kW rating is selected to meet the active power demand. However, the generator kVA rating, reactance ($X_d'$ and $X_d''$), and excitation system shall be selected to suit the following:

- Continuous load is the kVA vector sum of active and reactive power

$$\left(\sqrt{\mathrm{kW}^2 + \mathrm{kVAR}^2}\right).$$

- Motor starting kVA is at a very low power factor.
- Nonlinear loads such as a variable-frequency drive (VFD) are present. Since the generator is designed for a sinusoidal load with a 5% harmonic distortion, the kVA rating needs to be derated or the design altered for higher distortion factors.
- Apply resistance grounding for the generator neutral. (This subject is covered in chapter 4.)

### 2.3.7 Power Supply for Monitoring and Control Systems

Power supply for monitoring and control systems shall be reliable, unaffected by voltage dip or sag and transients, and shall meet the requirements of load characteristics including voltage, frequency, and harmonics.

An uninterruptible power supply (UPS) is required for electronic, analogue, and digital control and monitoring systems. This consists of a rectifier to convert AC source to DC, battery, inverter, and static transfer switch. Normal AC power for control is through the inverter, which is filtered, regulated, and isolated from system disturbances. Typical nonredundant and redundant UPS systems are shown in figs. 2.2 and 2.3, respectively.

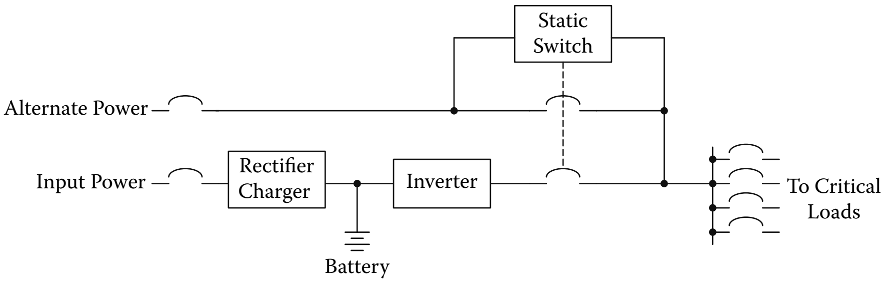


**FIGURE 2.2** Nonredundant UPS

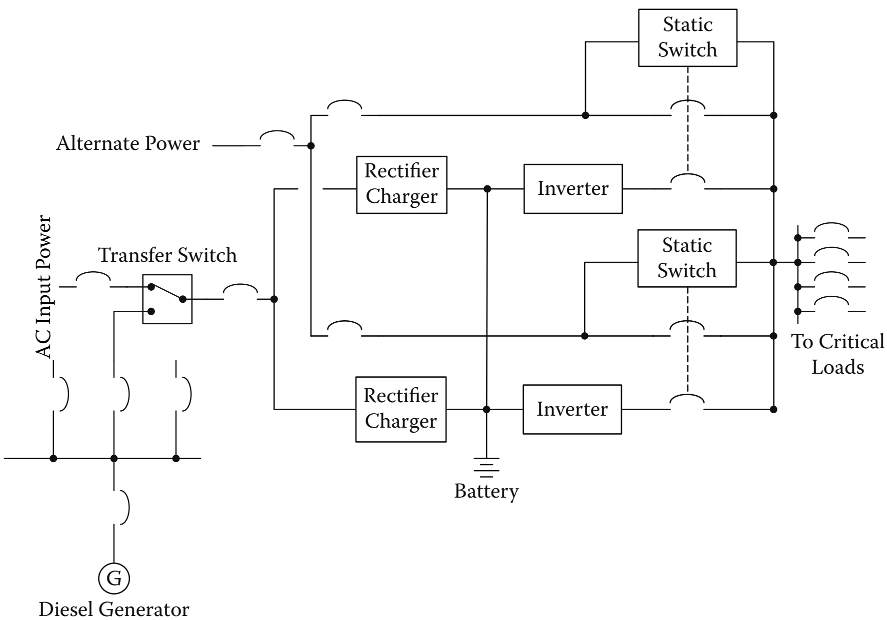


**FIGURE 2.3** Redundant UPS

In a nonredundant UPS, one charger and one inverter is used. In a redundant UPS, two chargers, two inverters, and an alternated AC source from an emergency or standby diesel generator are used to maintain the power supply under multiple contingencies.

### 2.3.8 DC Power Supply for Protection and Control

Power supply at 125 V DC is used for HV circuit breaker, medium-voltage switchgear, protection, control, monitoring, communications, emergency lighting, and emergency backup loads such as DC lube oil pump, etc. DC power supply consists of station battery, battery charger, and DC distribution. Selection and application of a station battery is covered in chapter 8.

## 2.4. DISTRIBUTION TYPES

Distribution systems commonly used in industrial plants are briefly described here.

### 2.4.1 Simple Radial

The simple radial system (fig. 2.4) has no redundancy and can be used where loss of power for an extended period is not detrimental to the process.

### 2.4.2 Expanded Radial

The expanded radial scheme (fig. 2.5) is an expansion of the above and has been used in many industries. The industrial power system at medium voltage (2.4 to 34.5 kV) is low-resistance (100–400 A) grounded, and power cable (insulated) is used for

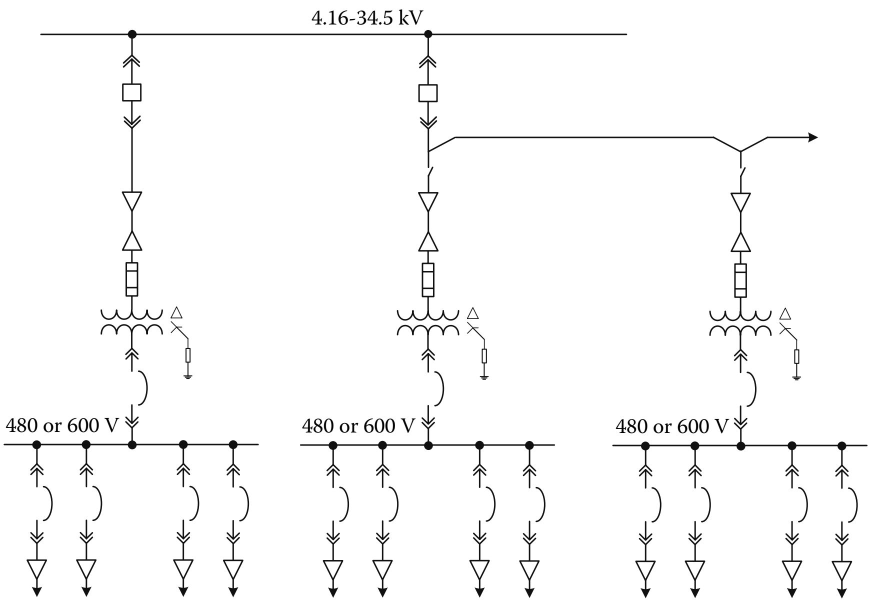


**FIGURE 2.4** Simple radial **FIGURE 2.5** Expanded radial

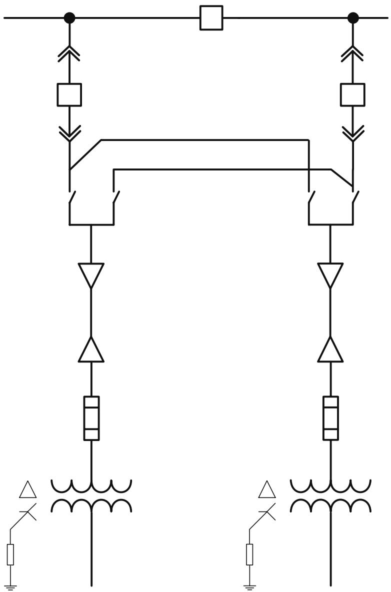

**FIGURE 2.6** Primary selective

distribution. The majority of the faults with cable systems start as a line-to-ground fault and escalate to a three-phase fault if not cleared within a reasonable time. On a line-to-ground fault, the fuse will either not see the fault current or will take a long time to melt. However, the ground-fault relay at the switchgear set at about 5% will trip the feeder breaker. The power is lost in a large area, and a longer time is required to detect and isolate the fault.

### 2.4.3 Primary Selective

In the primary selective arrangement (fig. 2.6), two primary feeders are brought to each substation transformer. Half of the transformers are connected to each of the two feeders. Each primary feeder is designed to carry the entire load. Though the problem caused by the line-to-ground faults is the same as with the expanded radial system, the power to the load centers can be restored quickly by transferring to the alternate feeder.

### 2.4.4 Secondary Selective

The secondary selective arrangement (fig. 2.7) can be achieved between two single transformer stations or double-ended stations by using a tie-circuit breaker. For low-voltage systems, the tie breaker is normally kept in open position, and an interlock between the main and the tie prevents paralleling of the transformers. An electrically operated manual transfer scheme can be used to close the tie breaker for a few cycles before tripping the selected main breaker. This scheme permits a planned shutdown of one transformer or primary feeder without dropping any load. However, the fault level may exceed the equipment rating during this brief period. Because both low-voltage buses are in an energized state, the possibility of developing a fault during this period is remote.

For medium-voltage systems, the tie breaker may operate in normally open or normally closed position. However, the relaying becomes more complex with parallel operation. The preferred and a commonly used arrangement is to operate the system with the tie breaker open and provide an auto- or manual-transfer scheme. The application of an auto-transfer scheme is common in thermal power plants.

### 2.4.5 Sparing Transformer

The sparing transformer scheme (fig. 2.8) is used where several low-voltage transformer stations of the same capacity are installed in one area. The load is transferred to the spare transformer upon the loss of any unit in the system. This minimizes the spare transformer capacity.

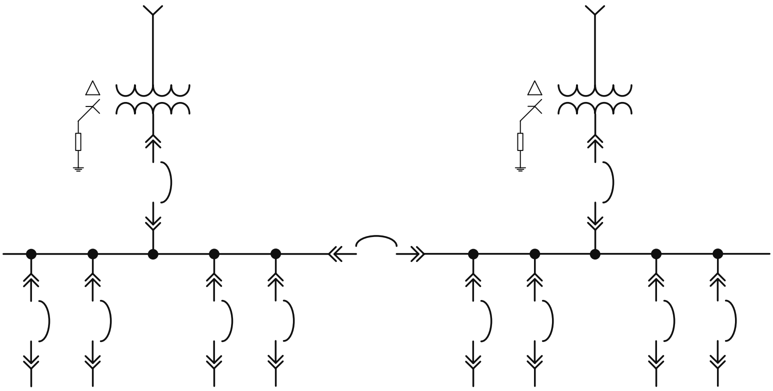

**FIGURE 2.7** Secondary selective

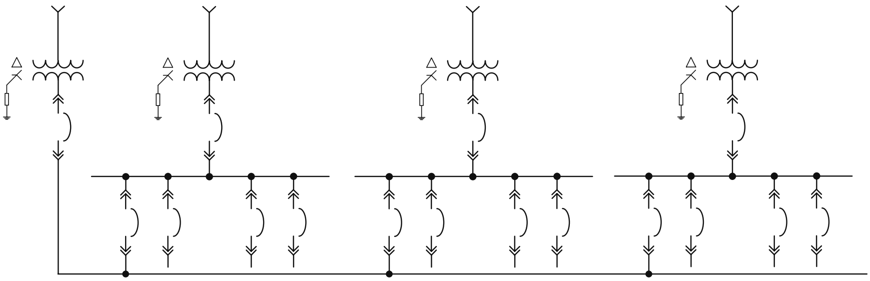

**FIGURE 2.8** Sparing transformer

## 2.5. PLANT POWER DEMAND AND LOAD ESTIMATE

### 2.5.1 Estimate of Power Demand and Energy Cost

Estimates of power consumption, power demand, and total power cost are carried out during the project feasibility stage and during the contract negotiations with the power utility. The results of the power cost study, the power consumption of utilization equipment, and the approximate location of equipment is required for system planning and sizing the electrical equipment.

The plant power demand, power cost, electrical load estimate in different areas, and selection of major electrical equipment can be made using the following approach.

#### 2.5.1.1 Energy Consumption or Average Kilowatt Hours Required for One Unit of Production

Historical data on energy consumption or average kilowatt hours required to produce one unit of product can be used for estimating:

- Energy consumption based on the plant output and operating hours
- Average power for the period
- Power demand for each facility and net demand for the plant

- Monthly and yearly power cost consisting of energy cost and demand charge:

$$\text{Avg. Power} = \frac{\text{kWh/unit} \times \text{Total Production}}{\text{Operating Hours}}$$

$$\text{Maximum Demand} = \frac{\text{Avg. Power}}{\text{Load Factor}}$$

An example illustrating the method for estimating the power requirement and power demand for an alloy steel plant producing 60,000 tons/year of finished product is given in tables 2.1 and 2.2, respectively. A plant producing Fe Cr (ferrochromium) operates 24 hours per day and 365 days per year, whereas the operating period for other plant facilities depends on the production requirement. These tables provide the plant operating period for each facility, including the number of shifts per day and number of days per week. Load factors and coincidence factors are based on past experience with similar plants.

Table 2.1 has been used to estimate the energy consumption and maximum power demand for each facility and total plant. Table 2.2 shows the plant facilities arranged in groups based on their operating period and shifts, which helps in organizing the plant operations and estimating plant manpower requirements.

Tariff as agreed with the power utility:

- \$6.00/kW of maximum power demand
- \$6.50/kW in excess or less than 80% of contract demand
- \$0.04/kW for energy consumed.

*Estimate of power cost*:

Power demand (based on a 30-min period) as derived from table 2.1 = 39,200 MW

Energy consumption per year = $166.3 \times 10^6$ kWh

Energy consumption per month = $13{,}860 \times 10^3$ kWh (based on an average 730 h)

Energy cost per month = $\$0.04 \times 13{,}860 \times 10^3 = \$554{,}400$

Demand charge per month = $\$6.0 \times 39{,}200 = \$235{,}200$

Total power cost per month = \$789, 600

#### 2.5.1.2 Typical Demand Factors for Utilization Equipment

Typical demand factors for utilization equipment are given in table 2.3.

$$\text{Total Power Demand} = \sum (\text{Equipment Rating} \times \text{Demand Factor})$$

added space between equipment and rating.

$$\text{Net Power Demand} = \frac{\text{Total Power Demand}}{\text{Coincidence Factor}}$$

**TABLE 2.1**
**Estimate of Power Requirement (Basis — 60,000 ton/yr)**

| Department/Facility | Operating | Period, h/yr | Production, ton/yr $10^3$ | Energy, kWh/ton | Consumption, kWh/yr $10^6$ | Avg. Power, kW | Load Factor | Max. Demand (30 min) |
|---|---|---|---|---|---|---|---|---|
| Fe Cr plant | Continuous | 8,760 | 18 | 4,000 | 72 | 8,220 | 0.9 | 9,130 |
| Arc furnace | 330 d/yr | 7,920 | 80 | 500 | 40 | 5,050 | 0.3 | 17,000 |
| V.O.D. | 330 d/yr | 7,920 | 80 | 10 | 0.8 | 101 | 0.2 | 505 |
| Continuous casting | 330 d/yr | 7,920 | 77 | 15 | 1.2 | 152 | 0.4 | 380 |
| Slab grinding | 3 shifts/d 5 d/week | 6,240 | 73 | 28 | 2.1 | 340 | 0.5 | 680 |
| Hot mill | 16 h/week | 832 | 72 | 65 | 4.7 | 5,650 | 0.65* | 8,700 |
| Coil preparation | 3 shifts/d5 d/wk | 6,240 | 55 | 27 | 1.5 | 240 | 0.5 | 480 |
| Cold mill | 330 d/yr | 7,920 | 55 | 320 | 17.6 | 2,230 | 0.6 | 3,720 |
| Hot annealing and pickling | 3 shifts/d5 d/wk | 6,240 | 54 | 55 | 3 | 480 | 0.6 | 800 |
| Skin pass mill | 2 shifts/d 5 d/wk | 4,160 | 40 | 140 | 5.6 | 1,350 | 0.65 | 2,080 |
| Slitting | 2 shifts/d 5 d/wk | 4,160 | 40 | 35 | 1.4 | 340 | 0.6 | 570 |
| Leveling and cutting | 5 d/wk | 4,160 | 28 | 65 | 1.8 | 440 | 0.6 | 730 |
| Strip grinding | 3 shifts/d 5 d/wk | 6,240 | 16.5 | 160 | 2.6 | 420 | 0.6 | 700 |
| Services | … | 7,920 | 60 | 130 | 7.9 | 1,000 | 0.8 | 1,250 |
| **Total** | … | … | … | … | **166.3** | **26,673** | | **47,605** |
| Overall annual operation | … | 8,760 | 60 | 2,772 | 166.3 | 18,990 | 0.484 | 39,200 |
| Excluding Fe Cr plant | … | 8,760 | 60 | 1,572 | 94.3 | … | … | … |

*Note:* Overall coincidence factor = 0.823 (diversity factor = 1.215). Overall coincidence factor is based on assuming 1.0 for Fe Cr plant and 0.781 for other loads.

**TABLE 2.2**

**Estimate of Power Demand (Basis — 60,000 ton/yr)**

| Department/Facility | Operating Period | Production, ton/yr $10^6$ | kWh/ton | Max. Demand, kW | Coincidence Factor for Group | Max. Demand for Group | Group No. | Operation Shift [a] |
|---|---|---|---|---|---|---|---|---|
| Fe Cr plant | Continuous | 18 | 4000 | 9130 | 1 | 9130 | 1 | 1, 2, 3 |
| Arc furnace | 330 d/yr | 80 | 500 | 17000 | 1 | 17885 | 2 | 1, 2, 3 |
| VOD | 330 d/ yr | 80 | 10 | 505 | | | | |
| Cont. casting | 330 d/yr | 77 | 15 | 380 | | | | |
| Cold mill | 330 d/yr | 55 | 320 | 3720 | 1 | 3720 | 3 | 1, 2, 3 |
| Hot mill | 16 h/wk | 72 | 65 | 8700 | 1 | 8700 | 4 | 3, 1 |
| Slab grinding | 3 shifts/d, 5 d/wk | 73 | 28 | 68 | 1.15 | 3080 | 5 | 1, 2, 3 |
| Coil preparation | 3 shifts/d, 5 d/wk | 55 | 27 | 04 | | | | |
| Hot annealing and | 3 shifts/d, 5 d/wk | 54 | 55 | 80 | | | | |
| pickling | | | | 80 | | | | |
| Cold annealing and | 3 shifts/d, 5 d/wk | 70 | 58 | 08 | | | | |
| pickling | | | | 80 | | | | |
| Strip grinding | 3 shifts/d, 5 d/wk | 16.5 | 160 | 700 | | | | |
| Skin pass mill | | 40 | 140 | 2080 | 1.15 | 2900 | 6 | 3, 1 |
| Slitting | 2 shifts/d, 5 d/wk | 40 | 35 | 570 | | | | |
| Leveling and cutting | | 28 | 65 | 700 | | | | |
| Services | … | … | … | 1250 | 1 | 1250 | 7 | 1, 2, 3 |

[a] Times for shift nos.: shift 1, 7:00 a.m.–3:00 p.m.; shift 2, 3:00 p.m.–11:00 p.m.; shift 3, 11:00 p.m.–7:00 a.m.

**TABLE 2.3**
**Demand Factors for Utilization Equipment**

| Equipment | Demand Factor, % | Equipment | Demand Factor, % |
|---|---|---|---|
| Arc furnace | 90–100 | Paper mills | 55–70 |
| Compressors | 30–90 | Refineries | 55–70 |
| Conveyors, blowers/fans | 80–90 | Welders, resistance | 10–40 |
| Lighting | 100 | Heating equipment | 85–95 |
| Cranes | 30–50 | Induction furnace | 85–95 |
| Welders, arc | 30–50 | Pumps | 50–70 |

### 2.5.1.3 Estimate of Power Demand from Equipment List

Load data extracted from the equipment list prepared by the process and mechanical engineers is used for sizing the secondary distribution equipment, including transformers and motor control centers.

## 2.5.2 Factors Used for Load Estimate and Power Demand

$$\text{Average Power} = \frac{\text{Energy Consumed during a Specified Period (kWh)}}{\text{Operating Period in hours}}$$

$$\text{Load Factor} = \frac{\text{Average Load for a Period}}{\text{Peak Load for the Same Period}}$$

$$\text{Demand Factor} = \frac{\text{Maximum Demand}}{\text{Connection Load}}$$

$$\text{Coincidence Factor} = \frac{\text{Maximum Demand}}{\text{Sum of Individual Demand}} < 1.0$$

$$\text{Diversity Factor} = \frac{\text{Sum of Individual Max. Demand}}{\text{System Max. Demand}} = \frac{1}{\text{Coincidence Factor}} > 1.0$$

# 2.6 VOLTAGE CONSIDERATIONS

## 2.6.1 Voltages Used in North America

The most common (preferred) system and utilization voltages used in the United States and Canada for industrial power systems are given in table 2.4. The power supply frequency is 60 Hz. Reference [S1] provides the voltages and their ranges. For utilization equipment, the voltage variation is defined in the relevant standards.

**TABLE 2.4**
**Preferred Voltage Level for Industrial Plants (Used in North America)**

| Voltage Class | System Voltage Highest | System Voltage Nominal | Transformer Voltage-Primary or Secondary at No Load [a] | Generator Rated Voltage [b] | Motor Rated Voltage | Remarks |
|---|---|---|---|---|---|---|
| Low | … | 120/208Y | 208 primary<br>208 Y / 120 sec. | | 208 | |
| | | 240 | 240 | | 220 | single phase in Canada |
| | | 480 | 480 | 480 | 460 | |
| | | 600 | 600 | 600 | 575 | |
| Medium | | 2 400 | 2 400 | 240 | 2300 | not a preferred voltage |
| | 4 760 | 4 160 | 4 160 | 4160 | 4000 | |
| | | | | | 4160 | synchronous |
| | 8 250 | 7 200 | 7 200 | 7200 | 6900 | not a preferred voltage |
| | 15 000 | 13 800 | 13 800 | 13800 | 13200 | |
| | | | | | 13800 | synchronous |
| | | 25 000 | 25000 | | | |
| | | 27 600 | 27600 | | | |
| | 38 000 | 34 500 | 34500 | | | |
| | 48 300 | 44 000 | 44000 | | | utility |
| | 72 500 | 69 000 | 69000 | | | distribution |
| High | 145 000 | 120 000 | 120 000 | | | transmission |
| | 170000 | 161 000 | 161 000 | | | |
| | 245 000 | 230 000 | 230 000 | | | |
| EHV | 362 000 | 245 000 | 345 000 | | | transmission |
| | 550 000 | 500 000 | 500 000 | | | |

[a] Transformer rated voltage (primary/secondary) is at no load.
[b] Generator rated voltage is higher (15 to 24 kV) for large machines.

### 2.6.2 Voltages Used in Europe

Preferred system voltages used in Europe are given in ref. [S6]; power supply frequency is 50 Hz. The preferred system voltages are summarized in table 2.5.

### 2.6.3 Voltage and Frequency Used in Other Countries

Most of the countries have adopted IEC standards for preferred voltages for system and equipment. However, some countries use a combination of old and new standard voltages. Power system voltages used in countries other than North America and Europe are given in table 2.6. For a complete list and current status, refer to Siemens or other relevant publications.

**TABLE 2.5**
**Preferred Voltage in IEC Standard**

| Voltage Classification | Normal Voltage | Highest System Voltage |
|---|---|---|
| >100 V, <1000 V | 230/400 | … |
| | 400/690 | |
| >1 kV, <35 kV | 3 | … |
| | 6 | |
| | 10 | |
| | 20 | |
| | 35 | |
| >35 kV, <245 kV | 69 | 72.5 |
| | 115 | 123 |
| | 138 | 145 |
| | 230 | 245 |
| >245 kV | | 362 |
| | | 420 |
| | | 550 |
| | | 800 |
| | | 1050 |
| | | 1200 |

*Source:* IEEE 446-1987, IEEE Recommended Practice for Emergency and Standby Power Systems.

## 2.6.4 Voltage Drop and Flicker

The performance of the utilization equipment (motors, lighting, etc.) is guaranteed when the voltage and frequency applied to its terminals is within the limits specified in the standards. Because the variation in power frequency is negligible during steady-state conditions, the voltage spread from no load to full load, transient voltage dips during switching operations (such as starting a large motor), and voltage flicker caused by cyclic loads such as reciprocating compressors need to be checked. Chapter 2 of ref. [1] has covered the effect of voltage spread on different utilization equipment.

### 2.6.4.1 Steady-State Voltage Drop

The steady-state voltage drop is caused by the variation in utility power supply and by voltage drop in the transformer and feeders connected to the utilization equipment. The spread from the utility power supply is generally remedied by utilizing main step-down transformers with load tap changers.

The electrical safety codes, NEC and CSA, have specified the allowable voltage drop at the maximum load current; these are 5% for feeders and 3% for branch circuits. The steady-state voltage drop can be calculated or estimated using one of the following methods.

- **Formula**
  Phase-to-neutral voltage drop is given by the formula:

$$\Delta V_{LN} = E_S + (I_R \times \cos\theta + I_X \times \sin\theta) + \sqrt{E_S^2 - \left(I_X \times \cos\theta - I_R \times \sin\theta\right)^2}$$

**TABLE 2.6**
**System Voltage Used in Countries Other than Europe and North America**

| Country | Frequency, Hz | Transmission, kV | Distribution, kV | Utilization, V |
|---|---|---|---|---|
| Afghanistan | 50 | 110 | 6, 15, 20, 33 | 220/380 |
| Algeria | 50 | 30, 60, 90, 150, 220, 400 | 5.5, 10, 15, 20, 33 | 220/380 |
| Argentina | 50 | 27, 33, 66, 132, 145, 170, 220, 500 | 6.6, 13.2, 13.8, 27 | 220/380 |
| Australia | 50 | 22, 33, 66, 88, 110, 132, 220, 275, 330, 500 | 3.6, 7.2, 11, 22, 33 | 250/440, 240/415 |
| Bahamas | 60 | 33, 66 | 2.4, 7.2, 11 | 115/200,120/208 |
| Bahrain | 50, 60 | 66, 220 | 6.6, 11, 33 | 240/415 |
| Bangladesh | 50 | 33, 66, 132, 230 | 11, 33 | 230/400 |
| Barbados | 50 | 24.9 | 3.3, 11 | 110/190, 120/208 |
| Brazil | 60 | 24, 33, 44, 69, 88, 138, 230, 345, 440, 500, 750 | 2.4, 4.16, 6.6, 11.5, 13.2, 13.8 | 110/220, 220/440, 127/220, 220/380 |
| Chile | 50 | 23, 44, 66, 110, 154, 220, 500 | 3.3, 5, 6.0, 6.9, 12, 13.2 | 220/380 |
| China | 50 | 33, 60, 110, 220, 380, 420, 500 | 6, 10 | 127/220, 220/380 |
| Colombia | 60 | 34.5, 44, 66, 115, 230, 500 | 2.4, 4.16, 6.6, 7.2, 11.4, 13.8 | 110/220, 150/260, 480 |
| Costa Rica | 60 | 24.9, 34.5, 69 | 13.2 | 120/208, 120/240, 127/220, 254/440 |
| Cuba | 60 | 33, 66, 110, 220 | 2.4, 4.16, 6.0, 6.3, 7.2, 13.2, 22 | 120/240, 231/400, 277/480, 440 |
| Dominican Republic | 60 | 34.5, 69, (138) | 4.16 | 110/220 |
| Ecuador | 60 | 24, 34.5, 46, 69, 115, 138, 230, 380 | 2.4, 4.16, 6.9, 13.8 | 120/208, 127/220 |
| Egypt | 50 | 33, 66, 132, 220, 500 | 3, 6, 10, 11, 33 | 400, 380/220 |
| Ethiopia | 50 | 45, 132, 220 | 15, 33 | 380/220 |
| Federation of Arab Emirates | 50 | 132, 220 | 6.6, 11, 33 | 220/380, 240/415 |
| Ghana | 50 | 33, 161 | 3.3, 6.6, 11 | 380/220 |
| Haiti | 50, 60 | … | 7.2, 12.5 | 110/220, 220/380 |
| Honduras | 60 | 34.5, 69, 138, 230 | 2.4, 4.16, 6.6, 13.8 | 110/220, 127/220 |
| India | 50 | 33, 66, 132, 220, 400 | 3.3, 6.6, 11 | 242/420 |
| Indonesia | 50 | 20, 69, 150, 500 | 6, 20 | 127/220, 220/380 |
| Iran | 50 | 66, 132, 230, 400 | 6, 11, 20, 33 | 220/380 |
| Iraq | 50 | 33, 66, 132, 400 | (3.3), (6.6), 11, 33 | 220/380 |
| Israël | 50 | 33, 110, 161, 380 | 6.3, 12.6, 22 | 220/380 |
| Ivory Coast | 50 | 30, 90, 220 | 5.5, 15 | 380/220 |
| Jamaica | 50 | 66 | 2.2, 3.3, 11 | 110/220, 440 |
| Japan | 50, 60 | 33, 66, 77, 110, 138, 154, 187, 220, 275, 500 | 3.3, 6.6, 11, 13.8, 22, 33 | 100/200, 400, 110/220, 440 |
| Jordan | 50 | 33, 66, 132, 230, 400 | 6.6, 11, 20 | 220/380 |

**TABLE 2.6**
**System Voltage Used in Countries Other than Europe and North America**

| Country | Frequency, Hz | Transmission, kV | Distribution, kV | Utilization, V |
|---|---|---|---|---|
| Kenya | 50 | 66, 132, 275 | 3.3, 11, 33 | 415/240 |
| Korea (north) | 60 | 66, 110, 220, 400 | 3.3, 6, 10 | 220/380 |
| Korea (south) | 60 | 66, 154, 345 | 3.3, 6.6, 11, 13.2, 23, 33 | 100/200, 220/380, 440 |
| Kuwait | 50 | 33, 132, 300 | 3.3, 6.6, 11 | 240/415 |
| Lebanon | 50 | 33, 66, 150, 230 | 5.5, 6, 11, 20 | 110/190, 220/380 |
| Liberia | 60 | 24.5, 69 | 12.5 | 120/240, 120/208 |
| Libya | 50 | 33, 66, 150, 220, 400 | 6, 10 | 380/220 |
| Malaysia | 50 | 33, 132, 275 | 6.6, 11, 22 | 230/400 |
| Mexico | 60 | 23, 34.5, 69, 85, 115, 230, 400 | 2.4, 4.16, 6.6, 13.8 | 120/208, 120/240, 127/220 |
| Mongolia | 50 | 110, 220 | 6, 10 | 220/380 |
| Morocco | 50 | 60, 72.5, 150, 220 | 5.5, 6, 20, 22 | 220/380 |
| New Zealand | 50 | 22, 33, 50, 66, 110, 220 | 3.3, 6.6, 11, 22, 33 | 230/400 |
| Nigeria | 50 | 66, 132, 330 | 3.3, 6.6, 11, 33 | 415/240 |
| Pakistan | 50 | 33, 66, 132, 230, 500 | 6.6, 11 | 230/400 |
| Panama | 60 | 34.5, 115, 230 | 2.4, 4.16, 13.8 | 110/220, 120/240 |
| Philippines | 60 | 34.5, 69, 115, 138, 230, 500 | 2.4, 3.3, 4.16, 4.8, 6.24, 13.8, 23, 34.5 | 110/220, 440 |
| Qatar | 50 | 66, 132 | 6.6, 11, 33 | 240/415 |
| Saudi Arabia | 60 | 33, 69, 115, 132, 380 | 4.16, 11, 13.8 | 220/380, 240/415, 127/220 |
| Singapore | 50 | 66, 230 | 6.6, 11, 22 | 230/400 |
| South Africa Republic | 50 | 88, 132, 220, 275, 400 | 3.3, 6.6, 11, 22, 33, 44, 66 | 550, 500, 380/220 |
| Sri Lanka | 50 | 33, 66, 132 | 3.3, 11 | 230/400 |
| Sudan | 50 | 66, 110, 220 | 6.6, 11, 33 | 415/240 |
| Syria | 50 | 66, 230, 400 | 6, 6.6, 11, 20 | 115/220, 220/380 |
| Taiwan | 60 | 69, 161, 345 | 3.3, 6.6, 11, 22, 33 | 110/220, 220/380 |
| Thailand | 50 | 69, 115, 132, 230, 500 | 3.3, 11, 22, 33 | 220/380 |
| Trinidad | 60 | 33, 66, 132 | 2.3, 4, 12, 13.8 | 110/220, 115/230, 230/400 |
| Tunisia | 50 | 30, 90, 150 | 10, 15, 22, 30 | 380/220 |
| Turkey | 50 | 66, 154, 380 | 6.3, 10, 20, 34.5 | 220/380, 110/190 |
| Venezuela | 60 | 34.5, 69, 115, 138, 230, 400 | 2.4, 4.16, 4.8, 6.6, 8.3, 12.4, 13.8, 24 | 120/,208, 120/240, 240/480 |
| Vietnam | 50 | 66, 132, 230 | 6.6, 13.2, 15, 35 | 220/380 |

where

$E_S$ = sending end voltage, phase to neutral

cos θ = power factor

R = sum of the resistance component in the circuit, ohms

X = sum of the reactance component in the circuit, ohms

A commonly used formula for percent voltage drop is

$$\Delta V = I \times \left(R \times \cos\theta + X \times \sin\theta\right)$$

or

$$= kVA \times \frac{(R \times \cos\theta + X \times \sin\theta)}{(10\ kV)^2}$$

- **Ampere-foot Method**
  This method can be used in computing the voltage drop in low-voltage feeders and branch circuits that have not been included in load-flow runs. In this method, the load current is multiplied by the one-way cable length to get the value in ampere-feet. The voltage drop can be read from the graphs in ref. [1] or estimated from the tables in ref. [11] against the cable size. The conductor size can be increased or the load can be fed from a different bus to reduce the voltage drop. Table 2.7, extracted from ref. [11], can be used for estimating voltage drop in a three-phase system with the load current at 0.8 power factor.
- **Load Flow**
  This is a system planning and study activity, and it is covered in chapter 3. The output files provide bus voltage summary for light or no load, full load, and contingency operations. The output files also highlight the bus voltage when it is in violation of the specified range. The transformer voltage spread or voltage drop from no load to full load is reduced by adjusting the transformer taps.

### 2.6.4.2 Voltage Flicker

The voltage changes of a transient nature, such as turning loads on and off, which last only a short duration, are generally referred to as voltage flicker. The rapid voltage fluctuations affect the light output from incandescent lamps, which can irritate the human eye. Flicker-limit curves adopted by IEEE and used by many power utilities in North America are shown in fig. 2.9 [S1]. These curves are the composite of the flicker on incandescent lamps studied by General Electric Co., Kansas City Power and Light Company, T&D Committee, Detroit Edison Company, and West Pennsylvania Power Company.

Flicker is divided into four groups based on their frequency of occurrence:

- *Cyclic flicker*: is that resulting from periodic voltage fluctuations, the range of frequency of fluctuation is 10 per second to 2 per second. Reciprocating compressors and pumps, arc furnaces, and automatic spot welders fall into this category.