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Electric Power Distribution
for
Industrial Plants

FOURTH EDITION



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Published by
THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.
345 East 47th Street, New York, N. Y. 10017



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PREFACE

The purpose of this publication is to promote the use of sound engineering principles in the design of electric systems for industrial plants. It explains what is good electrical practice today, but is not a handbook of design data. Because there are a great number of different types of industrial plants, it is impractical to cover in detail all the varied electric systems required. This publication treats those features of the electric distribution system which are applicable to most types and sizes of industrial plants.

The first edition of Electric Power Distribution for Industrial Plants was published in 1945 by the American Institute of Electrical Engineers. It was widely accepted by the engineering profession. The second edition was published in 1956, and represented substantial additions and revisions. The third edition brought up to date the practice resulting from technical developments since publication of the second edition. The present edition, the fourth, incorporates minor modifications.

It is anticipated that in addition to its usefulness to electrical engineers this publication will be informative to others involved in the design of industrial plants; the process engineers, architects and managers who are responsible for decisions affecting the electric system.

Comments, corrections and suggestions for future revision of this publication are welcome. They should be submitted to the Industrial and Commercial Power Systems Committee of The Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, N. Y. 10017.

Industrial Plants Power Systems Subcommittee
of the Industrial and Commercial Power Systems Committee
of the IEEE Industry and General Applications Group

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THE FOURTH EDITION

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ELECTRIC POWER DISTRIBUTION FOR INDUSTRIAL PLANTS

CHAPTER I

SYSTEM PLANNING

An industrial plant is only as good as its electric distribution system. For this reason, careful system planning for an industrial power system is very important. This chapter outlines the procedures of system planning and presents a guide which will make the details of succeeding chapters more useful and understandable. As has been often quoted, "If you can see the problem in your 'mind's eye', the rest is A, B, C."

A standard electric distribution system is not adaptable to all industrial plants because no two plants have identical requirements. Methods must be used to analyze the specific requirements of the industrial plant qualitatively and quantitatively, and design the system which will most adequately meet the electrical requirements of the particular plant, with consideration given to both present and future operating conditions.

BASIC DESIGN CONSIDERATIONS

Any approach to the problems must include several basic considerations which will affect the overall design. They are:

1. **Safety**—Safety takes two forms; safety to personnel and safety to materials, buildings and electric equipments.
Safety to personnel involves no compromise; only the safest system can be considered.
Safety to materials, buildings and electric equipments may involve some compromise where safety of personnel is not jeopardized.
2. **Reliability**—The continuity of service required is dependent on the type of manufacturing or process operation of the plant. Some plants can easily tolerate momentary outages while others require a very high degree of service continuity. In view of this, the system should be designed to isolate faults with a minimum disturbance to the system and should have features to give the maximum dependability consistent with the plant requirements.
3. **First Cost**—While first cost is important, it is often minimized if the system is reliable and its operation satisfactory. It should not be the determining factor in the design of the plant since distribution cost represents only 2 to 10 percent of the plant investment.

4. **Simplicity of Operation**—Simplicity of operation is a big factor in the safe and reliable operation of a plant. Avoid complicated and dangerous switching operations under emergency conditions.
5. **Voltage Regulation**—For some plant power systems, voltage spread may be the determining factor of the distribution design. Poor regulation is detrimental to the life and operation of electric equipment.
6. **Maintenance**—A well designed distribution system, with properly chosen equipment, will reduce emergency maintenance. In planning the system, the accessibility and availability for inspection and repairs should be given careful consideration.
7. **Plant Expansion**—Plant loads generally increase. Consideration of the plant voltages, ratings of equipment, space for additional equipment and capacity for increased load must be given serious study.

Planning Guide for Distribution Design

With the above factors in mind, the following procedure is given to guide the engineer in the design of an electric distribution system for any industrial plant.

1. Obtain a general layout and mark it with the major loads at various locations and determine the approximate total plant load in horsepower, kilowatts, and kilovolt-amperes.
2. Estimate the lighting, air-conditioning, and other loads from known data and the system load survey information given on pages 10 and 11.
3. Determine the total connected load and calculate the maximum demand by using demand and diversity factors.
4. Investigate unusual loads, such as the starting of large motors, operation of arc furnaces or welders, and operating conditions such as boiler auxiliary motors, loads that must be kept in operation under all conditions, and loads that have a special duty cycle.
5. Investigate the various types of distribution systems and select the system or systems best suited to the requirements of the plant. Make a preliminary one-line diagram of the power system.

6. If power is to be purchased from the utility, obtain such information concerning the supply system or systems as: performance data, voltage available, voltage spread, type of systems available, method of system neutral grounding, and other data such as relaying, metering and the physical requirements of the equipment. The interrupting rating and momentary ratings of power circuit breakers should be obtained as well as the present and future short-circuit capabilities of the utility system at the point of service to the plant. Investigate the utility's power contract to determine if off-peak power at lower rates is available, and any other requirements, such as power factor and demand clauses, that can influence power cost.
7. If considering a generating station for an industrial plant, such items should be determined as: generating kva required including standby loads, generating voltage, and such features as relaying, metering, voltage regulating equipment, synchronizing equipment and grounding equipment. If parallel operation is contemplated, be sure to review this with the utility and obtain its requirements.
8. A cost analysis may be required of the different voltage levels and various arrangements of equipment to justify and properly determine the voltage and equipment selected. The study should be made on the basis of installed cost including all the components in that section of the system.
9. Check the calculations of short-circuit requirements to be sure that all breakers are of the correct rating. Review the selectivity of various protective devices to assure selectivity during load or fault disturbances.
10. Calculate the voltage spread and voltage drop at various critical points.
11. Determine the requirements of the various components of the electric distribution system with special attention given to special operating and equipment conditions.
12. Review all applicable national and local Codes for requirements and restrictions.
13. Check to see that the maximum safety features are incorporated in all parts of the system.
14. Write specifications on the equipment and include a one-line diagram as a part of the specifications.
15. Obtain typical dimensions of equipment and make drawings of the entire system.
16. Determine if the existing equipment is adequate to meet additional load requirements. Check such ratings as voltage, interrupting capacity, and current-carrying capacity.
17. Determine the best method of connecting the new part of the power system with the existing system so as to have a minimum outage at minimum cost.

Naturally the above procedure will not automatically design the electric power system in itself; it must be used with good, sound, basic engineering judgment.

General Layout

A general layout of the plant should be available before the engineer can begin his study. This layout usually gives the location and the size of the proposed building or buildings in the initial particular project. The extent of the available layout gives the engineer an idea of the possible expansion of the plant in the future, and must be considered by the engineer in planning the electric distribution system.

Types of Circuit Arrangements

Most modern industrial plants make use of the load-center system. This system generally consists of several small substations receiving power from a medium- or high-voltage system and stepping down at the substation to utilization voltages at the various load areas. The use of many small substations introduces the possibility of many different circuit arrangements. Since the type of circuit arrangement selected will have an important effect on power system performance, cost, and reliability, it is a factor which must be considered in the system planning stage.

The basic types of circuit arrangements together with their respective characteristics are discussed in detail under Selection of Circuit Arrangements on page 18.

Plans for Future Expansion and Modernization

When plant facilities have to be expanded or modernized, the engineer is afforded an opportunity to design his ideal electric system. First, a one-line diagram should be prepared showing the type of system which would be used for a new plant of similar design. Having made the plan, he should let it guide the future modernization and expansion. Existing equipment obviously cannot be retired at once, but as additions and replacements of equipment are required, they should be made on the basis of being integrated in the ideal plan and not as replacements for the old system.

Flexibility

Plants change manufacturing processes from time to time. Where castings are used today, welding may be used tomorrow. Both process and product may change as demands and styles change. The electric distribution system for any plant should be flexible enough so that complete new process layouts can be made without requiring major changes in the distribution system.

Flexibility for expansion should be considered. In line with this, the engineer should strive for a system design that will permit reasonable expansion with minimum investment and minimum downtime to existing production.

Two great contributions toward flexibility are: (1) the load-center system with small substations which may be added in small blocks as required and (2) plug-in busway which permits the installation of flexible permanent power distribution systems on which machine tools and other devices are merely plugged in where necessary.

System Reliability

Service reliability in any plant is important. Most manufacturing processes are on a production-line basis so that a line shut-down may hold up an entire plant. Also some processes in themselves require a very high order of service reliability. Many factors influence the reliability of electric supply in the plant. Among the most important factors are the following: (1) Reliability of bulk power supply from utility and/or local generation; voltage fluctuations usually occur more frequently than momentary or sustained interruptions. Faults on the supply system can cause momentary voltage depressions in the supply voltage which may adversely affect industrial equipment; (2) Plant distribution system arrangement; (3) Simplicity of system

arrangement; (4) Simplicity of system operation and maintenance; (5) Reliability of equipment and installation. All of these factors should be considered in designing a system to meet the service reliability requirements of a given system. A study of equipment reliability is reported in Reference 5.

Selection of Equipment

The fundamental consideration in selecting equipment is to choose the optimum equipment consistent with the requirements of the plant. Frequently it costs no more in the long run to use the best equipment available as it pays dividends in service continuity and lower maintenance. Some widely accepted principles are:



Figure 1.1
Industrial unit substation installation of 7500 kVA with load-tap-changing equipment and outdoor metal-clad switchgear

1. Use of metal-clad and metal-enclosed equipment.
2. Choose nonflammable or dry type transformers for indoor installations.
3. Use factory-assembled equipment for easier field installation and better coordination.
4. Be sure equipment ratings are adequate in every respect, such as voltage, current, momentary, and interrupting rating.

Figure 1.1 shows a typical industrial unit substation incorporating these features.

Economics

Economics is a very important part of power system

engineering. The engineer must compare systems on the basis of cost as well as other features. In making economic comparisons, it is important to include all parts of the system from the power source down to and including the utilization equipment.

Economic comparisons should also include installation as well as equipment and operating costs. As an example: system A may require less transformer kVA than system B, but the connections of system A and other factors may require far more expensive switchgear and more cable than system B. The increased cost of switchgear and cable may more than offset savings in transformer equipment. A comparison on the basis of transformers only would give the wrong answer. (Reference 6)

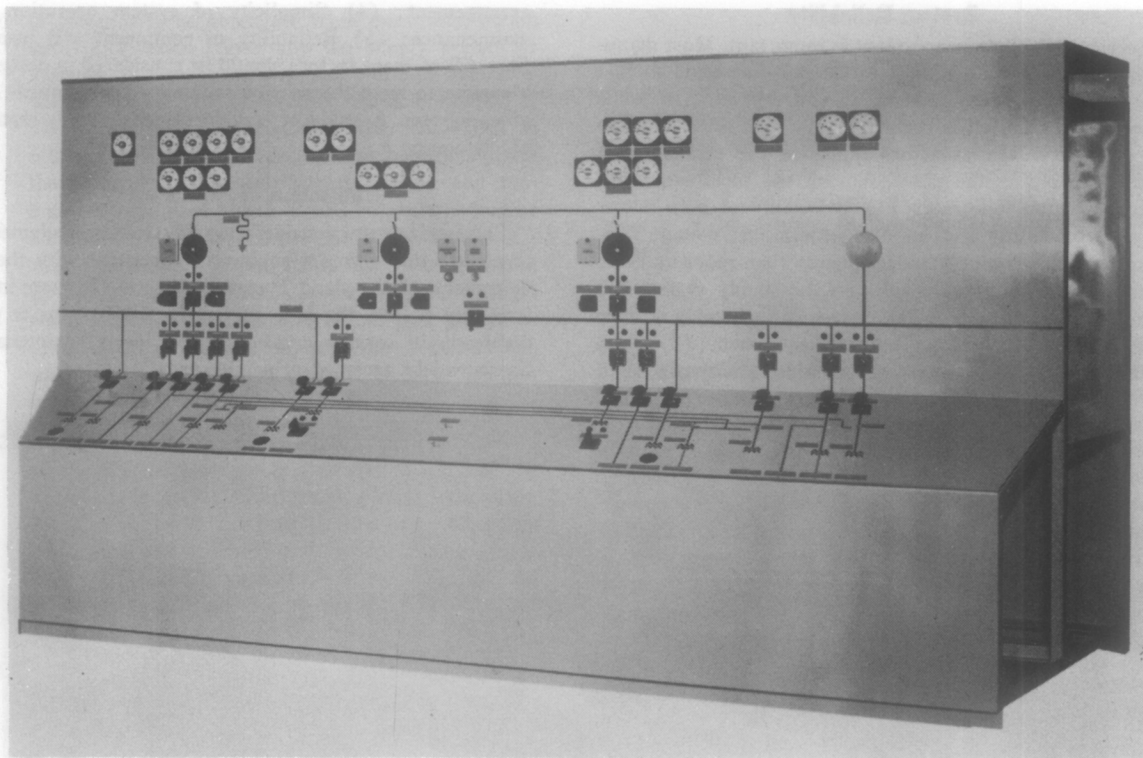


Figure 1.2
A central control benchboard for the main 13.8-kV power distribution system of an industrial plant

Operation and Maintenance

Proper maintenance is as important to successful performance of the system as selection of the system and its components. Long after the first cost is forgotten the maintenance cost will continue and, if foresight has not been used, this cost may be considerable.

Figure 1.2 shows a centralized controlboard. The mimic bus and organized arrangement of components can be a real aid in avoiding operating errors.

Although maintenance is largely in the hands of the operators, the system designer can aid in the problem by designing systems that can be maintained economically with a minimum of downtime or provide alternate power circuits.

One circuit can then be taken out for maintenance without dropping essential load. Also, drawout equipment should be used wherever possible to enable maintenance on breaker elements to be done in a service shop.

Another important factor to consider is that maintenance costs often can be reduced by care in locating equipment and by providing convenient auxiliary services. As an example, adequate aisles should be provided and spares of vulnerable parts should be accessible. Provisions should be made for auxiliary power and light so that vital services can be continued during periodic maintenance work.

Other important considerations are location and routine operation and setting of devices. Switchboards, circuit breakers, panelboards, and similar equipment, should not be located where they are subjected to accumulations of dirt, dust and other foreign materials or where they may be damaged by cranes or factory trucks. Operation and

settings of relays should be checked regularly. The design engineer can help by including suggested maintenance schedules in the data given to the operator.

Utility Service

In designing the power distribution system, thought must also be given to the utility service. This service must be reviewed from the standpoint of voltage level and also voltage spread, as discussed in Chapter II.

If the supply voltage is 15 kV or less, it is frequently used without transformation. Voltages above 15 kV are generally considered too high for use within buildings and, hence, transformation is required in these cases. When transformation is necessary, there is a problem of selecting the proper primary voltage—i.e., 2.4, 4.16, 6.9 or 13.8 kV. The choice is usually based on economics and will greatly affect both the first cost and also the cost of future expansion of the distribution and utilization equipment. In general, 4.16 kV is chosen for loads less than 10,000 kVA; 13.8 kV is chosen for loads above 20,000 kVA; and either might be selected for loads between 10,000 and 20,000 kVA, depending upon the possibility of expansion and concentration of the load. This subject is covered later under Selection of System Voltage on page 17.

Voltage spread in the utility system may be troublesome depending upon the type of utilization equipment involved. If the primary voltage variation is excessive, then feeder or bus voltage regulators may be required. These may be load-tap-changing transformers, individual regulators, switched capacitors or secondary feeder regulators. The choice is based upon both economic and engineering considerations.

DETERMINATION OF LOADS

General

Determination of the load is the electrical engineer's first problem and may be difficult to solve. The size and number of primary and secondary substations, the size, number and arrangement of primary feeders, and the type of secondary distribution, are largely dependent on the amount and nature of the load and its distribution.

The plant distribution system usually must be designed before all loads are known. This is at a time when the equipment layout itself is only in the formative stage. Equipment may be bought piecemeal during which time changes in machines are taking place either in number or size. Ideas are changed by the impact of what is commercially available, or by manufacturers' recommendations for improved models, better ways of securing a given result, or by competitive conditions. Processes themselves are being changed as available equipment is fitted into the prospective production schedule.

Many plants are built to manufacture new products, which adds to the difficulty of establishing power requirements. Plant layouts are subject to considerable modification of the original scheme. Entire plant rearrangement may be necessary in the middle of a job; air and refrigerating compressors, fans, blowers and pumps may come into the picture or shift position rapidly; oil-fired annealing furnaces may become electrically heated as a result of laboratory tests that prove a controlled atmosphere necessary, thus adding hundreds if not thousands of kilowatts to the plant load.

Even after a plant is in operation, loads may change in size and location. New models, new products and production methods call for continual change in the distribution system, but these changes can be minimized by careful planning.

Preliminary Load Survey

How to make preliminary estimates of loads is a problem deserving the closest study. These estimates may have to be used as the basis for major decisions. At this stage in the plant design, the electrical engineer often has available only a few building layout drawings or perhaps a plant map. The general locations of the major pieces of equipment will usually be roughly indicated and their power requirements may or may not be known. Starting with this information the electrical engineer must call on all his knowledge and experience as well as on that of other plant engineers and designers to enable him to arrive at an estimate which will stand up as the loads become better defined. In most cases, it is better to consider the lighting and power loads separately and combine them later to determine the demand in any one area, since present practice is usually to supply these loads from a load-center substation.

Factors most frequently used in determining distribution system loads are as follows:

Demand Factor: The ratio of the maximum demand on a system to the total connected load of the system. (The maximum demand is usually the integrated maximum

kilowatt demand over a 15 or 30 minute interval, rather than the instantaneous or peak demand.

Diversity Factor: The ratio of the sum of the individual maximum demands of the various parts of a system to the maximum demand of the whole system.

Load Factor: The ratio of the average load over a designated period of time to the peak load occurring in that period.

Information as to the demand and the diversity factors for the various loads and groups of loads is needed to design the system. For example, the sum of the connected loads on a branch load circuit, multiplied by the demand factor of these loads, will give the maximum demand which the branch circuit must carry. The sum of the maximum demands of the branch circuits associated with a sub-load center or panelboard divided by the diversity factor of those branch circuits will give the maximum demand at the sub-load center and on the circuit supplying it. The sum of the maximum demands of the circuits radiating from a load center, divided by the diversity factor of those circuits, will give the maximum demand on the transformer at the load center. The sum of the maximum demands of the load-center transformers divided by the diversity factor of the transformer loads will give the maximum demand on their primary feeder. By the use of the proper demand and diversity factors as outlined above, the maximum demands on the various parts of the system from the branch load circuits to the power source, inclusive, can be determined.

Lighting Loads

Estimating the lighting is usually not difficult. For rough estimates, only the area of the building and the illumination level desired need be known. For more accurate estimating, the general type of construction must be known as well as mounting height and spacing and location of roof trusses and columns, so that the optimum arrangement can be checked against physical requirements. The intensity of illumination and the type of lighting (mercury, fluorescent, or incandescent) desired together with general construction features will make possible computation of load using formulas in lighting handbooks or data from fixture manufacturers.

For quick estimates of lighting with the most efficient fluorescent units, approximately three watts per square foot will provide 50-footcandle illumination. If incandescents are used, the wattage will be approximately twice as much.

Information on outdoor lighting is readily available. Fence lighting can be estimated at 200 watts per 100 feet. "Yard lighting" is often adequate if a 200-watt lamp is placed every 100 feet along the exterior walls of buildings. The total outdoor lighting will seldom exceed 25 percent of all lighting and it may be as little as 5 percent; hence, a rather nominal allowance in primary substation and feeder capacity will provide for considerable leeway for changes in the outdoor lighting which may develop late in the construction period.

Table 1.1 gives lighting requirements in various industries.

Table 1.1
Lighting Requirements in Various Industries

<i>Industry</i>	<i>Lighting in Percent of Total Connected Load</i>
	Percent
Steel Foundries	1 to 3
Steel Rolling Mills, Oil Refining	3 to 5
Heavy Electric Equipment, Wire	
Drawing	5 to 8
Auto Equipment, Baking	8 to 10
Machine Parts	10 to 15
Auto Assembly and Parts	15 to 25

The diversity factor of the lighting load will be low and the demand factor of the lighting connected to any load center should be considered as 100 percent.

Power Loads

Estimating the power load is considerably more difficult than estimating the lighting load. Table 1.2 gives estimated load densities in representative industries.

Table 1.2
Estimated Load Densities in Various Industries

<i>Type of Plant</i>	<i>Voltampere Demand Light and Power</i>
Airplane Factories	15 to 25 VA/sq ft
Beet Sugar Factory and Refinery	19 "
Paper Mills	14 "
Textile Mills, Engine Builders	12 "
Cigarette Manufacturing	11 "
General Manufacturing, Chemicals,	
Electronic Equipment	10 "
Small Appliance Manufacturing, Machine	
Repair Shop	7½ "
Lamp Manufacturing	5 "
Small Device Manufacturing	3½ "

Table 1.2 should be used for preliminary estimating only since the size of the plant and its processes will vary considerably within a given industry category.

When the loads of individual machines or areas are known, it is necessary to combine them to obtain the maximum demand. The maximum demand determines the system capacity which must be provided to supply it as well as optimum system voltage. It is determined by applying demand and diversity factors to the connected load. The selection of demand and diversity factors, like load density, is based on known conditions, experience, and similar operations in existing plants. Table 1.3 gives the factors for the more common types of manufacturing loads and is the factor by which the connected load must be multiplied to obtain total plant demand assuming diversity factor of one. If the diversity factor is known, the demand thus obtained should be divided by the diversity factor to obtain the actual demand.

Table 1.3
Demand Factors

<i>Load</i>	<i>Estimating Demand Factor—Percent</i>
Arc Furnaces	100
Arc Welders	30
Induction Furnaces	80
Lighting	100
Motors	
1. General Purpose, Machine Tool, Crane Elevators, Ventilation, Compressors, Pumps, Rolling Mills, etc.	30
2. Semi-continuous Processes, Paper Mills, Refineries, Rubber Mills, etc.	60
3. Continuous Operations, Textile Mills, Chemical Plants, etc.	90
Resistance Ovens, Heaters and Furnaces	80
Resistance Welders	20

As the table shows, the demand factor will vary considerably with different types of loads. For example, the demand factor of a group of motors driving a conveyor belt will approach 100 percent, while the demand factor of a group of hand tools in a small furniture factory or machine shop might be only 10 percent. A diversity factor of unity is often used to provide ample system capacity, since the margin provided in this way is soon used by load growth. Although a diversity factor of unity represents the sum of the maximum demands of the individual load centers and of the equipment applied at the distribution voltage on the distribution system, the usual practice is to provide a system adequate for a maximum demand obtained with a diversity factor of unity or to provide even more than 100 percent capacity in the main system to take care of load centers which would be added in the future.

Any of a wide variety of plants may come under consideration in making a load survey. A knowledge of approximate kva load necessary to produce unit weights of the material being made is a great help. This knowledge may come from past experience or available published material. It would be impossible to list all types of industries here, but requirements for some of the more important industries follow:

Table 1.4
Bulk Product Industries

<i>Kilowatthours Per Pound of Product</i>	
Gasoline	0.0015
Liquid Sulphur Dioxide	0.002
Glycerine (from soap)	0.005
Ammonium Phosphate	0.007
Sulphuric Acid	0.016
Formaldehyde	0.030
Tri-Sodium Phosphate	0.038
Portland Cement	0.050
Ethylene Oxide	0.070
Alumina Ex Bauxite	0.090
Nitric Acid	0.180
Synthetic Ethyl Alcohol	0.300
Electric Steel	0.330
Carbon Disulphide	0.450
Benzene Hexachloride	0.600

Ammonia, Chlorine & Caustic (salt electrolysis)	0.750
Phosphoric Acid (electric furnace).....	1.80
Rayon	2.50
Sodium	4.70
Hydrogen Peroxide }	
Electrolytic Magnesium }	8.0
Aluminum	9.0

Table 1.5
Unit Product Industries

Kilowatthours Per Unit of Product		
	<i>kWh</i>	<i>Unit</i>
Automobiles	1050	each
Carpets & rugs (wool)	1480	1000 sq yd
Cement	22	bbl.
Paper		
Wood Pulp	384	ton
Paper & Board	575	ton
Pig Iron	25	ton
Shoes	472	1000 pairs
Steel	227	tons
Sugar		
Beet	154	ton of refined sugar
Cane	220	ton of raw sugar
Tobacco		
Cigarettes	200	million
Cigars	8100	million

Electronic Data Processing Machines

Large computers require that special consideration be given to the electric distribution system supplying them. Special requirements are usually stipulated by the computer manufacturer, and requirements vary with computer design.

A typical computer will require 3-phase, 4-wire, 60-hertz supply at 208, 230 or 240 volts. Permissible voltage variation ranges from ± 3 to ± 10 percent, depending on computer design. Frequency variations permitted are in the order of $\pm \frac{1}{2}$ to ± 1 hertz. Computers in general are likely to be damaged by system transients which may otherwise go undetected. The degree of susceptibility varies with the computer design. It is usually advisable to feed the computer from a separate transformer, and in some cases it is necessary to isolate it further by the use of a motor-generator set.

Power requirements of typical large computer systems range from about 200 to 500 kVA, with air-conditioning requirements of from 25 to 75 kVA.

TRENDS IN DESIGN OF INDUSTRIAL POWER SYSTEMS

Trends Affecting Power System Arrangements

Three important trends in the design of industrial power systems which affect power system arrangement are: (1) the increased use of load-center systems, (2) the grounding of the system neutral at all voltage levels, and (3) the increased use of higher voltages (generally 480Y/277 volts) for lighting in industrial and commercial buildings. These three trends are reviewed below:

Load-Center Systems

A load-center system may be defined as one in which power is transmitted at voltages above 600 volts to unit substations located close to the centers of electric load. At these substations the voltage is stepped down to the utilization level and distributed by short secondary feeders to the points of use. The trend to this type of system as opposed to older types of systems has become very marked in recent years. An examination of the advantages listed below for the load-center system when compared to older systems will indicate why such a trend has come about.

1. Lower first cost.
2. Reduced power losses.
3. Improved voltage regulation.
4. Increased flexibility.
5. Better continuity of service.
6. Simplified engineering, planning, and purchasing.
7. Lower field installation expense.
8. Higher salvage value.

Load-center systems may employ any of the basic system arrangements for primary power supply. The five combinations most generally used are radial, secondary selective, primary selective, looped primary and secondary network. What system to use should be determined by a study of the requirements for each job. Various other types of system arrangements, such as primary network, have been used as well as combinations of the basic system arrangements, such as primary selective—secondary selective. It should also be pointed out that a contributing factor to the increased use of load center systems has been the development of air circuit breakers, metal-clad and metal-enclosed switchgear, and especially askarel-filled and dry type transformers. These equipments have permitted the installation of the unit substations in buildings and close to the centers of loads without requiring expensive vaults to minimize fire hazards and danger to personnel. Another factor has been use of the transformer and large motor scheme, switched and protected as a unit.

System Neutral Grounding

Grounding of system neutrals at primary voltages has been almost universally practiced. However, there have always been two schools of thought regarding grounding of system neutrals at utilization voltages. There are many systems in operation with ungrounded neutrals, but few such systems are being installed today. There is therefore, a trend toward neutral grounding at the lower voltages, and it is probable that most of the new systems from now on will be of the grounded-neutral type. The advantages claimed for system neutral grounding are:

1. Reduced operating expense.
2. Improved service reliability.
3. Greater safety.
4. Better system and equipment overcurrent protection.
5. Improved lightning protection.

The use of grounded-neutral systems affects power system design by requiring, through study and careful selection, a means of grounding. Selection of transformers of proper characteristics for the unit substations will usually be involved. In some cases lower rated lightning arresters may be used resulting in better surge protection. Ground relays are usually employed on high- and medium-voltage systems for faster relaying of faults.

Higher-Voltage Lighting

The use of higher-voltage lighting, such as 480Y/277 volts, is gaining favor for large industrial and commercial buildings. Fluorescent and mercury-vapor lamps which require ballasts or transformers regardless of supply voltage are well adapted to operation on the higher voltages. Reduction of the total installed cost is the principal objective. The savings to be made are a function of the size of the building and the percentage of the total load connected to the higher voltage.

Higher-voltage lighting will affect the design of the power system by reducing the number and size of low-voltage feeders operating at 120 volts, although it will not be practicable to eliminate such circuits entirely due to the need for convenience outlets for appliances. Likewise, step-down transformers from 480 to 120 volts will also be reduced in number and size. Where the lighting is of the incandescent type and more than half the load it may not be economical to use higher-voltage lighting, since incandescent lamps require transformers to permit their operation on lower voltages.

Trends Affecting Power System Equipment Application

The principal trends that affect equipment in the industrial power system include:

Metal-Enclosed Switchgear Assemblies

The high cost of construction labor in recent years has emphasized the need for purchasing factory-assembled equipment if maximum economy is to be achieved. This need plus the many unquestionable advantages of metal-enclosed switchgear has accelerated the trend toward its use in plants recently built or in the process of building.

Three types of metal-enclosed switchgear have evolved over a span of 40 years since this type of equipment was first introduced to the industry. The distinction between types is based on construction features and voltage classification. Metal-enclosed switchgear is available in either indoor or outdoor construction.

Metal-clad switchgear consists of completely metal-enclosed, grounded stationary structures in which the secondary control devices, main power bus and outgoing circuits are each isolated by means of grounded metal barriers to provide maximum reliability. The circuit interrupting devices are of the removable type and the buses, connections and joints are insulated throughout. Interlocks are provided to insure proper sequence and safe operation. Metal-clad switchgear is available for medium-voltage-class systems. Refer to Figure 1.3.

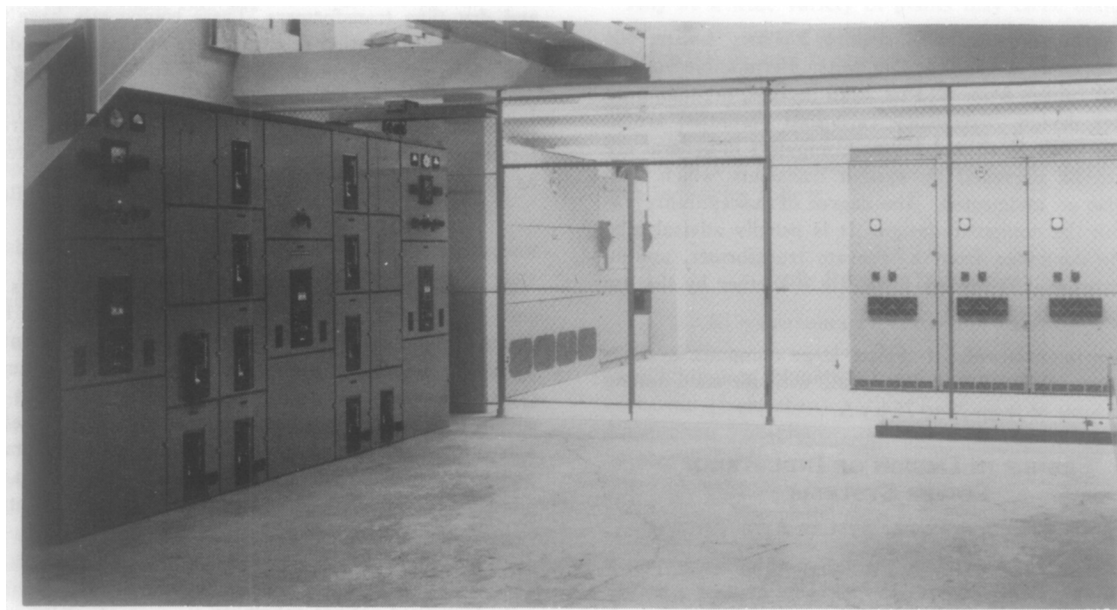


Figure 1.3
Indoor metal-clad switchgear with primary, transforming and secondary sections of a 3000-kVA unit substation.

Metal-enclosed load-interrupter switchgear consists of completely metal-enclosed, grounded structures with fixed or removable fused (or non-fused) load-interrupter switches. No metal barriers are used to isolate separate parts of the primary circuit. Buses, joints and connectors are non-insulated copper or aluminum mounted on suitable supports. The fused load-interrupter switch is designed to interrupt load current, and should be capable of safely closing against high fault currents. The fault-interrupting capacity and the high-current closing capability of the equipment are dependent on the characteristics of the associated fuses. Suitable interlocks can be provided to insure safe and proper operation. Metal-enclosed load-interrupter switchgear is also available for low- and medium-voltage-class systems.

Metal-enclosed, low-voltage switchgear consists of free standing metal-enclosed, grounded switchboard structures with low-voltage power circuit breakers contained in individual compartments. The circuit breakers are either stationary or drawout mounted and may be controlled remotely (electrically operated) or from the front of the switchgear. The buses are normally non-insulated and incoming and outgoing circuits are not normally barriered. Suitable interlocks are provided to insure safe and proper operation. As the name of this equipment implies, it is available for applications to low-voltage class systems.

A few of the advantages of metal-enclosed switchgear are:

1. Safety to personnel.
2. Ease of maintenance.
3. Ease of installation.
4. Compactness.
5. Lower installed cost.
6. Flexibility.
7. Ease of ordering.
8. Uniformity of appearance.

Power Circuit Breakers

Air circuit breakers are now almost universally used as opposed to oil circuit breakers for a wide variety of voltages, current-carrying and interrupting capacities to cover almost every requirement in an industrial plant or commercial building. They have established a good record for reliability, safety, and low maintenance costs.

Askarel and Dry-Type Transformers

The use of load-center systems has been facilitated by the development of transformers which can be installed in buildings close to centers of load without requiring expensive vaults. The askarel-insulated transformer is the most commonly used type in the industrial field and has the broadest range of application. It has the advantages over the ventilated dry type of about twice the impulse strength, a lower audio sound level, lower maintenance, and can be located outdoors or almost anywhere in the plant. This type transformer has one property superior to

oil-immersed transformers, in that the insulating liquid is non-flammable. Askarel is a non-oxidizing insulating fluid and when decomposed by an electric current evolves only non-explosive gaseous mixtures. These gases are toxic and rooms in which askarel transformers are located should be ventilated.

The developments in ventilated and sealed dry type transformers in the larger sizes have contributed to their increased use for unit substations. At the present time dry type transformers are readily available in ratings to 2000 kVA at 15 kV and below. The cost of ventilated dry type transformers is about 10 to 15 percent above that of conventional oil-insulated self-cooled transformers and is less than the cost of the askarel type. They are well adapted for use in clean locations.

Hermetically sealed dry type transformers filled with inert gas are available for use in less favorable locations. The cost is 35 to 40 percent more than the conventional oil-insulated self-cooled transformers but only 10 to 15 percent more than the askarel type. The hermetically sealed, Class H transformers, can be placed almost anywhere in a building provided adequate ventilation is available.

Cables

Rubber and rubber-like synthetic compounds used as insulation and cable coverings suitable for direct exposure to the elements and for direct burial in the ground are in common use at voltages up to 15 kV.

Synthetic compounds of the thermoplastic type, such as poly-vinyl-chloride and polyethylene, are being used at an increasing rate for low-voltage power and control cable insulations because of the excellent electrical and moisture-resistant properties as well as their relatively low cost. Such insulations have made possible the use of these cables in trays.

Medium-voltage insulations require, in addition, high dielectric strength and corona and ozone resistance. Thermosetting synthetic compounds such as butyl, silicone, and rubber compounds are being used to meet these requirements.

To protect insulating compounds which exhibit excellent electrical properties but lack the desired environmental resistance, polychloroprene compounds are being widely used for jacket material. Polychloroprene, a tough thermosetting synthetic compound, has a high resistance to chemicals likely to be encountered in service.

On medium-voltage cables, shielding is normally used for voltages in excess of 4 kV except for portable cables where shielding is normally used on cables above 2 kV.

The availability of the synthetic materials has created a trend away from underground duct systems and open wire on cross arms. Aerial cable, which is gradually replacing the duct and open-wire systems, is becoming quite popular for long outdoor circuits. Aerial cable is factory or field assembled from three or more properly insulated and jacketed conductors and a supporting messenger wire, which is effectively banded to the conductors. They are commonly made for voltages up to 15 kV grounded neutral and sizes up to 500 MCM. Advantages over the open-wire

system are fewer service interruptions, good appearance, ease of installation, less congestion on poles or towers, improved voltage regulation because of lower and balanced reactance, and reduced clearance requirements.

For indoor and short outdoor circuits, interlocked armor cables have found wide application at all voltage levels up to 15 kV. This cable eliminates the need for conduit, raceways, or duct and is frequently installed in troughs, baskets or racks. To help insure a low ground return circuit impedance, an interstitial equipment ground wire is recommended and sometimes required by local Codes. It has been found that the interlocked armor exhibits an appreciable impedance which causes stray currents to flow through building members and may result in sparking and thus create a safety hazard, unless internal grounding conductors or other effective grounding circuit is provided.

For a more complete discussion of cable practices, see Chapter IX.

Plug-In Busway

The use of plug-in busway is quite common for industrial buildings where changing loads must be accommodated. Factories, within which machines are likely to be moved around or changed frequently, provide excellent applications for the plug-in busways. Although the first cost of such an installation may be higher, future changes can be made at much lower cost and in less time.

Capacitors

Shunt capacitors are used to advantage in many industrial installations. Electric power contracts frequently contain power-factor clauses which benefit the plant if reasonably high power factor is maintained. The savings realized will often pay for the installation cost of the capacitors

within a short time. In addition, reduced voltage drop is realized, particularly if the capacitors are located near the loads. Likewise the power losses in feeders and branch circuits may be reduced because of lower currents flowing through them when the power factor is improved. This in turn achieves another benefit; the ability to carry additional connected load on the same feeder circuit.

Voltage Regulators

The spread in voltages supplied by the utilities, together with the voltage drops occurring in transformers, feeders, and branch circuits under load conditions, may result in a wide variation in voltage at the utilization devices between light load and heavy load conditions. The trend is to reduce such voltage variations to a minimum in order to obtain more satisfactory operation of the power utilization devices. Some of the larger industrial plants install voltage regulators on buses or feeders to maintain relatively constant voltages at the load. Transformers with load tap changing, have been used and are being increasingly applied when the incoming supply voltage is above 15 kV. While the trend is in the direction mentioned above, each case must be carefully studied to determine whether or not voltage correcting equipment can be economically justified.

Motor Control Centers

A strong trend has been established toward centralized motor control equipment. The advantages of grouping all motor controls at a central point are often present even when individual motor control units are used. Motor control centers have a number of advantages over the individually mounted controllers. The most important advantages are:

1. Reduced installation costs. Complete units assembled and wired at factory.

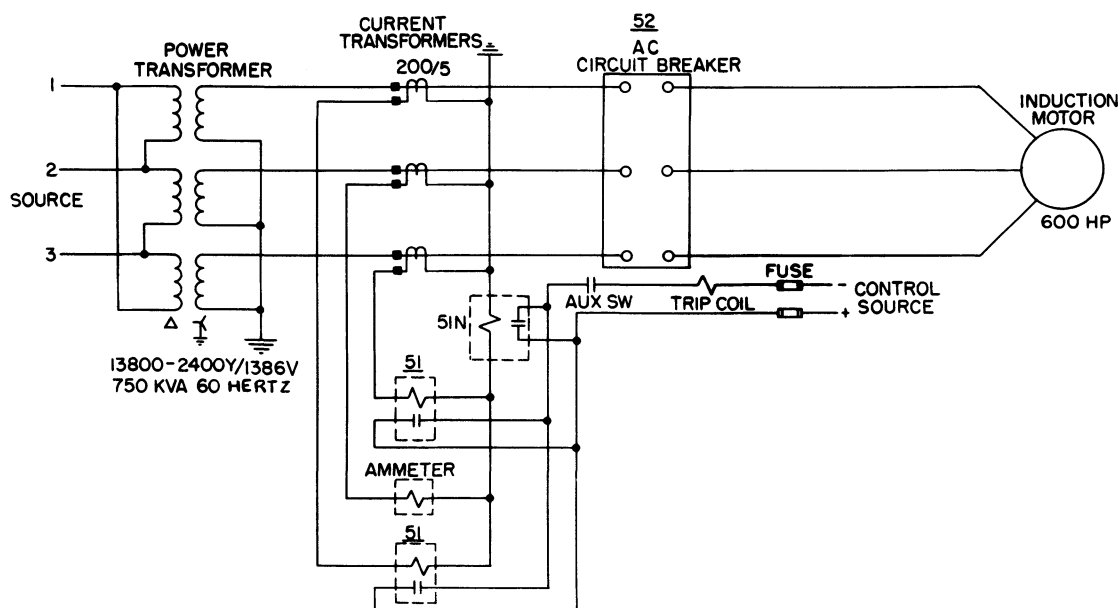


Figure 1.4
Three-line diagram

2. Flexibility. Because of modular type of construction, starters of various sizes can be readily interchanged on job.
3. Ease of maintenance. Starters may be removed for maintenance.
4. Increased safety. All units dead-front with interlocked doors.
5. Compactness.
6. Reduced engineering and purchasing costs.
7. Better protection against moisture, dirt, and mechanical injury.
8. Better appearance.

Prospective users of motor control centers should carefully study manufacturers' specifications to make sure that the equipment offered will be adequate for the duty involved. Preference should be given to standard construction. The economic advantage of motor control centers may be lost when special features are desired.

ONE-LINE DIAGRAMS

A one-line diagram is one which indicates, by means of single lines and simplified symbols, the course and component devices or parts of an electric circuit or system of circuits.

To illustrate, consider the simple circuit shown in Figure 1.4. This is a three-line diagram. It shows the details of an entire circuit. The complete paths of all currents can be traced through all the conductors and apparatus in the circuit.

However, in a general consideration of such a circuit wherein we are concerned mainly with the path of energy transfer (but not current paths) and the identification of circuit components with their ratings, the one-line diagram, Figure 1.5 serves the purpose better.

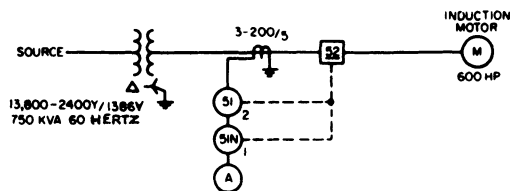


Figure 1.5
Simplified one-line diagram

In the preparation of preliminary plans for a system or specifications, it is not necessary to show all details in complete form on a one-line diagram.

Some of the more important items to be included as follows:

1. The available short-circuit and ground currents of power company's system.

2. The size, type, and number of incoming and outgoing cables.
3. The ratings, reactances, and connections of the transformers.
4. The points at which power is to be metered and the type of metering desired.
5. The amount and character of the load on all feeders.
6. Authentic information as to the exact geographical location of the installation.

Figure 1.6 illustrates a preliminary one-line diagram of a typical industrial power system.

The following items, if given special attention during preparation, insure complete, accurate, and lucid diagrams.

1. Keep the Diagram Simple

The one-line diagram should show the major electric circuits and components in the most simple form for ease of understanding. Equipment should be arranged to minimize the number of crossing lines without regard to the actual geometry of the plant. The geometry of the plant is of course important to keep in mind when making the one-line diagram. This geometry should be shown on a map, and a wiring diagram should be made later showing the actual location and routing of the circuits.

2. Avoid Duplication

The one-line diagram is a sort of "diagram shorthand," and for this reason every line, symbol, figure, and letter has a definite meaning and is made to serve some definite purpose in conveying significant information. Therefore, duplication should be carefully avoided. For example, when giving the rating of a current transformer, the abbreviation "CT" should not be used because the symbol itself conveys this information. It is sufficient to state merely the type and rating, thus "800/5." Even the abbreviation "AMP" after the rating is unnecessary, because current transformers obviously can be rated only in amperes.

3. Use Standard Symbols

The use of standard symbols and conventions is desirable. If special features occur which cannot be accurately covered by standard symbols and conventions, care should be exercised to make entirely clear the meaning of any nonstandard symbol or convention devised to cover such features.

4. Show All Known Facts

Details of circuits and devices known to the author of a diagram may seem to be unimportant or even irrelevant to him at the time. To someone else, however, or even to the author at a later date, these details may assume major importance, and their omission may be the cause of much extra work and loss of time, or even errors and misunderstandings. No detail within the scope of the diagram, therefore, should be considered as "unimportant," and the rule, "when in doubt, show it," should be followed.

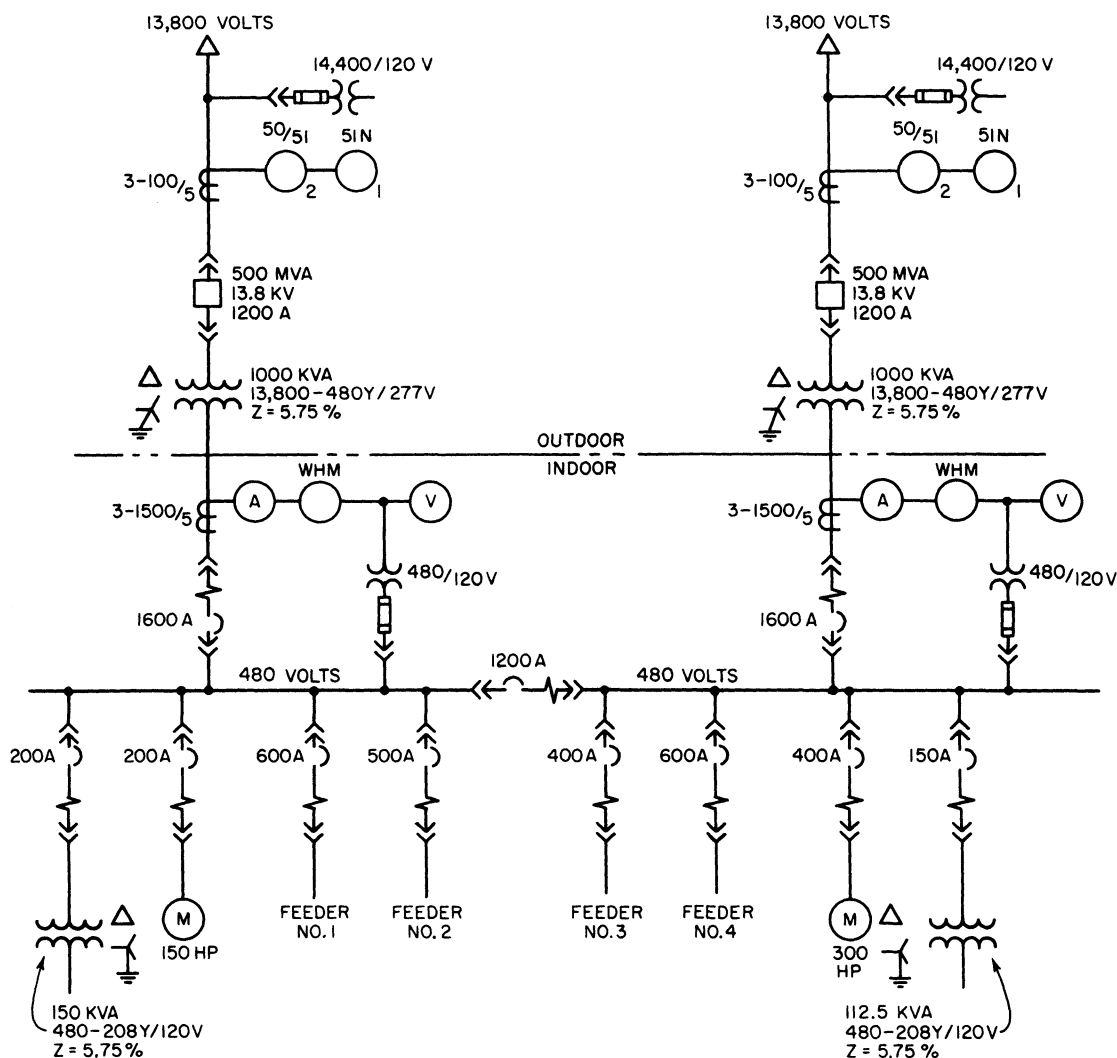


Figure 1.6
Typical one-line diagram

By checking the following list before releasing a diagram, the omission of some of the more important details can be avoided.

1. Manufacturer's type designations and ratings of devices.
2. Ratios of current and potential transformers, taps to be used in multi-ratio current transformers and potential transformers, connection of double-ratio current transformers.
3. Connections of power-transformer windings (i.e., wye, delta, etc.).
4. Circuit-breaker ratings in volts and amperes and (if not indicated by the manufacturer's type designation) the interrupting rating, type and number of trip coils on circuit breakers.
5. Switch and fuse ratings in volts and amperes.
6. Functions of relays.

7. Ratings of machines and power transformers.

8. Size and type of cables.

9. Voltage, phase, and frequency of all incoming circuits. A statement should accompany this information stating whether or not the neutral of any apparatus connected to the source is grounded. If grounded, the statement should specify whether the ground is solid or through an impedance. If the latter, the value of the impedance should be given.

5. Show Future Plans

Frequently, special features are devised which have no purpose in connection with the system being drawn at the time but which are included in equipment in order that it may fit into some plan for future changes or extensions. Such future plans should be set forth on the diagram either in diagrammatic form or by explanatory

notes. For example, an outdoor station structure is often built with two disconnecting switches in series in a given circuit with the intention of using them ultimately as isolating switches for a circuit breaker to be installed later. If shown without comment or the indication of the future breaker, the purpose of the second switch is entirely obscured.

6. Include Correct Title Data

Care should be exercised in the assignment of titles to one-line diagrams to the end that they may accurately identify the installation.

To all who contribute to the preparation of one-line diagrams this admonition is given:— "Tell what you know on the one-line sketch but nothing which you do not know. Other engineers are likely to mistake your guesses for your knowledge, often with disastrous results."

SELECTION OF SYSTEM VOLTAGE

The selection of utilization, distribution and sub-transmission voltage levels is one of the most important considerations in power system design. System voltages usually affect the economics of equipment selection and plant expansion more than any other single factor. It behooves the power system engineer to consider carefully the problem when designing the distribution system.

Voltage Classes

The various voltage levels may be broadly classified as follows:

- 1) 600 volts and less (low voltage)
- 2) 601 to 15,000 volts (medium voltage)
- 3) above 15,000 volts (high voltage)

The low-voltage class, is normally restricted to supplying utilization equipment directly. The medium-voltage class (commonly 2.4, 4.16, 6.9, and 13.8 kV) is used most frequently for distribution purposes but occasionally is employed as a utilization voltage, particularly for motors rated 2.3, 4.0, 6.6 or 13.2 kV. The high-voltage class, above 15,000 volts, may occasionally be encountered as the utility supply voltage. In a large plant, with widely dispersed load areas, voltages above 15,000 volts may be used to distribute power.

Factors Affecting Voltage Selection

The factors affecting system voltage selection are:

1. Service voltages available from utility
2. Load magnitude
3. Distance power is to be carried
4. Rating of utilization devices
5. Safety
6. Codes and standards

The relative effect of these factors varies widely depending upon the particular plant involved. In general, however, the following will apply:

Service Voltages Available From Utility—The best distribution voltage to use within a plant may not be one of the service voltages available from the utility at the plant site. When this situation arises, the system design engineer must determine the relative costs of using the service voltage, for distribution or providing sufficient substation transformer capacity to obtain the desired distribution voltage. In some cases, the necessary substation investment will prove uneconomical and one of the available service voltages will be used.

Load Magnitude—Load magnitude has little if any bearing on selection of voltages in the 600-volt class but is an important factor in selecting distribution voltages. It is usually the determining factor for selecting distribution voltages when the plant is compact and where the load is concentrated in one area. The utilization equipment voltage ratings and voltage limitations are almost the entire governing factor.

Distance Power Is to Be Carried—Distance does not usually affect selection of voltages in the 600-volt class but is an important consideration in the selection of distribution and sub-transmission voltages. It is particularly important when sizable loads are located at quite a distance from the main plant.

Rating of Utilization Devices—Utilization devices have a major effect on the selection of voltages in industrial plants. Incandescent lamps, small fractional horsepower motors, hand tools, business machines, appliances, etc. are generally available with 110-, 115-, or 120-volt ratings. Where this type of equipment is used, 120-volts single-phase must be available.

Three-phase motors are readily available for voltages from 208 to 13,200 volts. However, the most desirable voltage for a given motor from both a design and system cost standpoint varies with the horsepower rating. The horsepower ratings of three-phase motors definitely affect system voltage selection in both the low-voltage and medium-voltage classes. Other types of utilization equipment affect the selection of system voltages. For example, approximately 75 percent of furnaces using resistance elements are designed for 240 volts, with 480 volts generally maximum. Large arc-furnace transformers are generally limited to a maximum of 23 to 34.5 kV because of switching equipment limitations. This illustrates how utilization equipment other than lighting and rotating machinery can affect system voltage selection.

Safety—Safety is a major factor in selecting system voltage in the area of 120 volts, or below, where appliances and portable tools are used. For example, where there is a possibility of contact with energized parts such as in ungrounded frame portable tools, voltages of the order of 32 volts have been selected because it has been shown that voltages above 50 volts to ground can be lethal. This practice, in general, conforms to National Electrical Code. The grounding of all portable tools is recommended when permitted.

On circuits above 120 volts to ground there seems to be little concrete evidence that voltage selection from a safety standpoint is a major consideration. While the chances of electrocution do, to a certain extent, increase with an increase in voltage, these higher ratings can all electrocute a person if he contacts a live part under proper conditions. For the highest order of safety on circuits 50 volts and higher, work on current-carrying parts should be done only with the circuit de-energized.

Codes and Standards—The National Electrical Code places limitations on the voltage ratings of equipment and distribution circuits within buildings and should be consulted to assure conformance.

SELECTION OF CIRCUIT ARRANGEMENTS

General

The power systems engineer has a choice of many different circuit arrangements. Although the various arrangements may be compared on several bases, the choice usually resolves itself into the selection of an arrangement which will provide the required degree of service reliability at the minimum cost. In arriving at a satisfactory compromise between cost and service reliability, the following fundamental considerations should be kept in mind:

The cost of providing electric power to a particular area in an industrial plant includes fixed investment charges and capitalized losses in addition to the cost of the power itself. A great deal more can be done to control investment charges and losses than can be done to control the power cost. Thus, the principal concern when attempting to reduce over-all costs is with the initial investment.

In controlling initial investment, far more can be accomplished by proper selection of circuit arrangement than by economizing on equipment details. When cost reductions are necessary, they should never be made at the sacrifice of safety and performance by using inferior apparatus. Reductions should be obtained by using a less expensive distribution system with some sacrifice in reserve capacity and reliability.

The degree to which extra expenditures should be added to the plant distribution system to increase its service reliability depends upon (1) characteristics of the manufacturing process, and (2) reliability of the power source. Both of these factors must be considered in arriving at a solution to this problem.

Characteristics of Manufacturing Process—In many manufacturing plants, a short outage of power can be tolerated. In other plants, short outages of power result in the spoiling of considerable material in process or cause shutdowns over a large area. In the former cases, where short shutdowns can be tolerated, it is questionable if anything but the simplest system can be justified on an economic basis. In the latter cases, it might be possible to justify considerable expense for increasing the reliability of the distribution system.

Power Source Reliability—Service reliability at the point of utilization depends upon the reliability of the

power source. Therefore, every effort should be made to obtain a power source having a degree of reliability commensurate with plant requirements.

If the source circuits are cable, and particularly underground cable, the probability of faults in them will be much less than in overhead, open-wire circuits. However, while the frequency of occurrence is low, as much as 24 hours may be required to locate and repair the fault.

Faults on overhead open-wire circuits may be either transient or permanent in nature. In the case of transient faults, service is generally restored immediately by reclosing of the line breaker. Outages due to permanent faults may require about 8 hours to locate and repair.

It is important to keep in mind that service reliability figures are highly variable on various parts of a system and on various systems. Historical records of similar installations under similar conditions will provide a reasonable guide as to what to expect. (Reference 5.)

Types of Circuit Arrangements

There are many types of circuit arrangements possible, although the most commonly used power system arrangements can usually be classified as one of the following basic types:

1. Radial
2. Secondary-Selective
3. Primary-Selective
4. Looped-Primary
5. Secondary-Network

A brief discussion of each of these basic circuit arrangements follows:

Radial

In the radial arrangement, there is only one primary feeder and one transformer through which a given secondary bus is served. Earlier types of radial systems usually consisted of an outdoor transformer supplying the load through several low-voltage secondary feeders. A system of this type is shown in Figure 1.7.

Recently, however, there has been an increasing trend toward the load-center distribution type of radial system shown in Figure 1.8.

The load-center system differs from the earlier type in that power is distributed at primary voltages of 2.4 to 13.8 kV to substations located close to the centers of electric load. Here, the power is stepped down to utilization voltage (600 volts or less) and delivered by short secondary feeders to points of use. The load-center system offers several important advantages over the earlier type of radial systems and is usually the preferred arrangement except in small plants where floor space may be at a premium.

The radial-type circuit arrangement of the load-center system will be the least expensive in the majority of installations since there is no duplication of equipment.

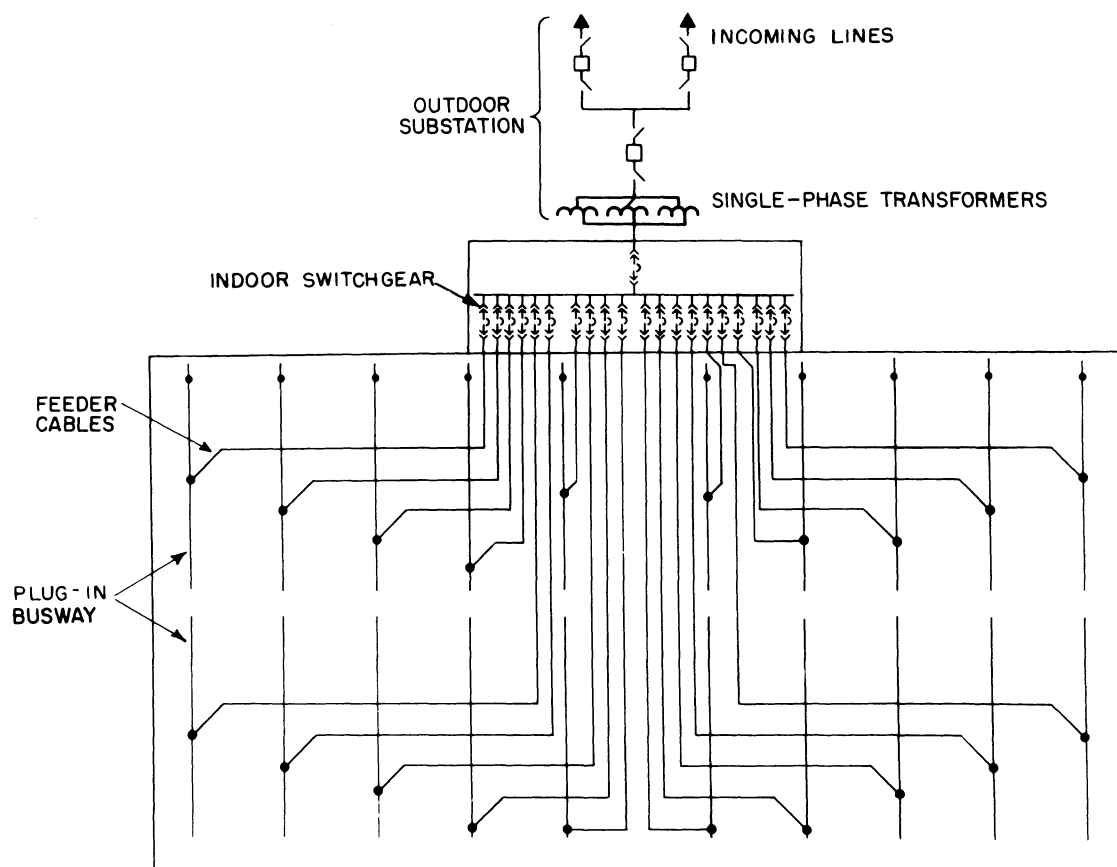


Figure 1.7
Old style distribution system for a medium size plant using one large substation and long secondary feeders

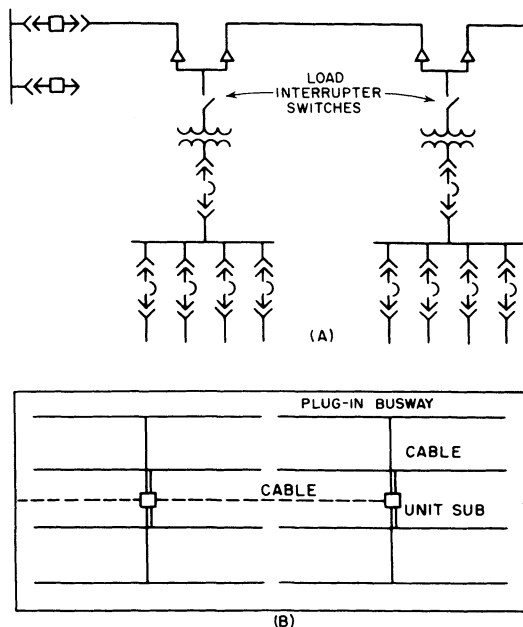


Figure 1.8
Typical radial circuit arrangement load-center distribution system
(A) one-line diagram (B) layout in plant

If sufficient substation capacity is used, the radial arrangement will adequately care for practically any diversity that will be encountered due to shifting of load. With adequate, properly installed equipment, the system is safe, simple, easy to operate and easy to expand by merely extending a medium voltage feeder, or adding a new feeder and substation. Good voltage regulation is provided because of the short secondary feeders.

It must be recognized that should a primary cable or transformer fail, service is lost to the area supplied by the faulty equipment until it is repaired. Furthermore, maintenance on primary feeders or transformers requires the complete de-energization of the area served by the equipment being maintained. Many engineers feel that the de-energization during maintenance is far more of a handicap than forced outages. Forced outages are so rare that temporary connections can be resorted to, if necessary, in order to keep essential loads in operation.

Secondary Selective

Two of the several possible arrangements of the secondary-selective system are shown in Figure 1.9. This system utilizes two primary feeder circuits and two transformers to supply each load-center area. This arrangement

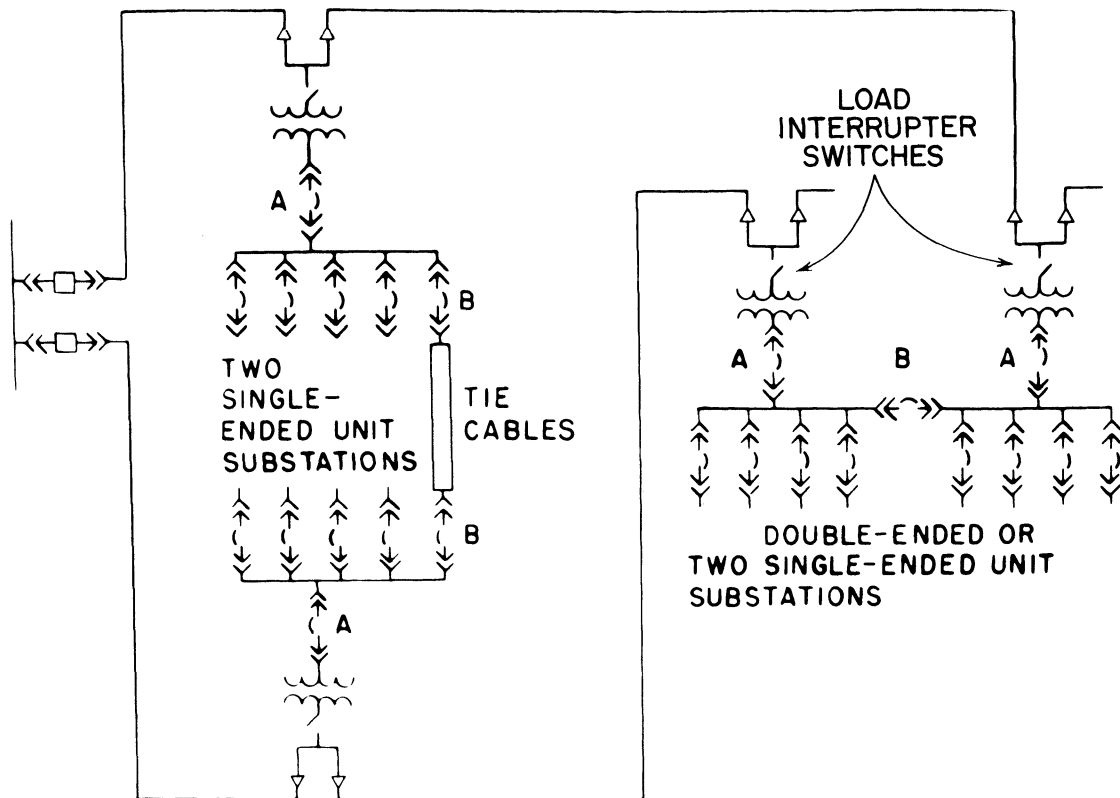


Figure 1.9
Typical secondary-selective arrangement of the
load-center distribution system

provides duplicate paths of supply from the source to each secondary bus and makes it possible to provide power at all secondary buses when a transformer or primary feeder circuit is out of service.

The secondary-selective arrangement may be achieved through a tie between two single-transformer substations or through the use of double-ended substations. The tie breaker is normally open and the system operates as two parallel radial systems entirely independent of each other beyond the power supply point. The tie breaker is normally interlocked with the two transformer breakers so that it cannot be closed unless one of the transformer breakers is open. This practice minimizes the short-circuit duty imposed on the low-voltage feeder circuit breakers.

Since the load is normally divided equally between the two bus sections, half of the load in the area is dropped in the case of a primary feeder fault. Service can be quickly restored to the interrupted loads by opening the transformer breakers associated with the faulted feeder and closing the bus-tie breakers at all load centers. If the system is to carry the entire plant load with one primary feeder circuit out of service, each primary feeder must be capable of carrying the entire load and sufficient reserve transformer capacity must be provided. The reserve transformer capacity installed will usually be based on the magnitude of essential loads.

Primary Selective

The primary-selective arrangement differs from the radial and secondary-selective systems in that two primary feeders are brought to each substation transformer as shown in Figure 1.10. Half of the transformers are normally connected to each of the two feeders. The system is designed so that when one primary feeder is out of service, the remaining feeder has sufficient capacity to carry the entire load.

With this arrangement, as with the secondary-selective arrangement, service to half of the load is interrupted when a fault occurs on a primary-feeder circuit. To restore service quickly to all loads following the loss of one feeder, the transformers normally supplied from the faulted feeder can be switched to the good feeder. In cases where the fault may be in a transformer, preferred operating procedure would be to open the circuit breaker on the energized feeder and switch one transformer from the other feeder to the good feeder. When this switching has been accomplished, the good feeder would be energized. This procedure would be followed until all transformers had been switched or until the feeder breaker tripped because the last transformer connected to it was faulted.

If switching is to be done while one primary feeder circuit is energized, the safest way to make the transfer from one feeder to the other is with adequate power circuit breakers. However, the cost of such an arrange-

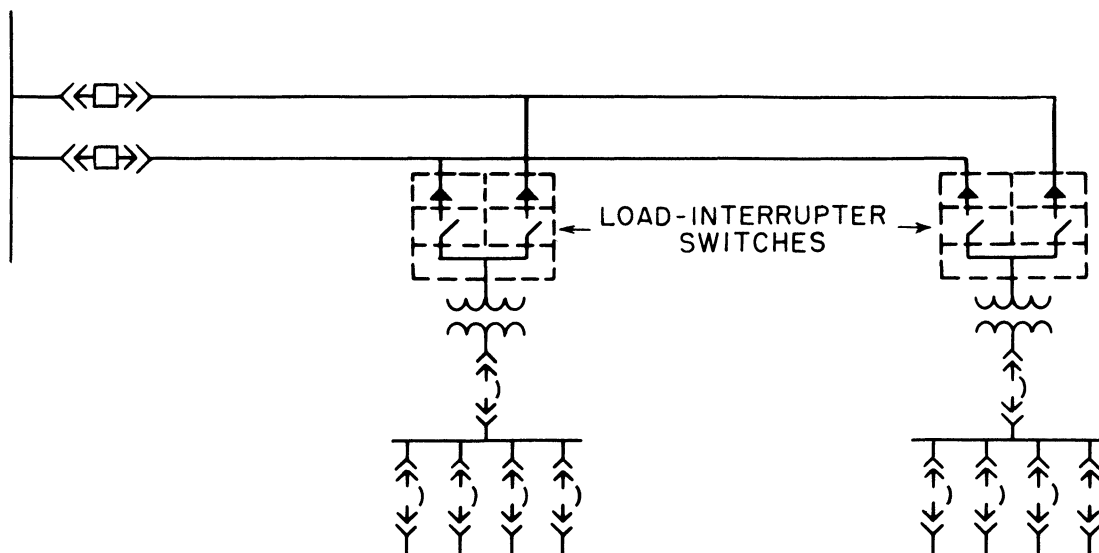


Figure 1.10
Primary-selective load-center system with two single-throw interlocked primary interrupter switches

ment is relatively high and normally is not used unless an automatic transfer scheme is desired. Usual practice is to use two load-interrupter switches properly interlocked, to accomplish the transfer from one feeder to the other.

The primary-selective system provides a higher degree of service reliability than the radial system and about the same as the secondary-selective system, depending on the amount of reserve transformer capacity installed in the secondary-selective system. The flexibility of this arrangement to handle shifting or growing loads is the same as the radial system assuming the same reserve transformer capacity in both system.

Looped Primary

The systems considered thus far have radial primary feeders. In cases where the centers of load are relatively far apart, the use of looped-primary feeders may offer some advantages. Figure 1.11 shows two forms of the looped-primary arrangement.

The looped-primary arrangement at the top of Figure 1.11 utilizes a single primary-feeder breaker and has one sectionalizing load-interrupter switch at each transformer while the lower loop arrangement utilizes two primary-feeder breakers and has two sectionalizing switches at each transformer. When a transformer or primary-feeder fault occurs in either loop arrangement, the primary-feeder breaker or breakers will open and interrupt service to all loads served from that loop. The fault can be located by opening all load-interrupter switches and closing them one at a time in sequence. It is strongly recommended that the primary-feeder breaker or breakers be open before operating any switch. This practice will eliminate the possibility of closing

the switch on a fault. Although modern load-interrupter switches have fault closing ratings deliberate closure on faults as with any switching device should be avoided.

When the fault has been located, it can be isolated from the system by leaving the appropriate load-interrupter switch or switches in the open position. In the upper loop arrangement, of Figure 1.11, one transformer and its loads must be out of service for a transformer fault or a fault in the loop between transformers until the fault is eliminated. In the lower loop arrangement, the only time that loads are subjected to an extended outage is in the case of a transformer fault. The two switches at each transformer make it possible to isolate any fault location on the loop and still provide service to all transformers.

The upper loop arrangement will cost little more than the radial arrangement and offers the advantage of providing service to all loads except those served from one transformer when either a transformer or primary-feeder fault exists on the system. The lower arrangement will have a lower cost than the primary-selective arrangement and will provide service to all loads when a primary-feeder fault has been isolated similar to the primary-selective arrangement. A transformer fault will cause an extended outage to the associated loads in either the looped-primary or primary-selective arrangement.

The main disadvantage of the looped-primary arrangement is that a primary-feeder or transformer fault will cause an interruption of service to all loads.

Secondary Network

The secondary-network system may take the form of either a distributed network or a spot network and either form may utilize a primary-selective feeder arrangement.

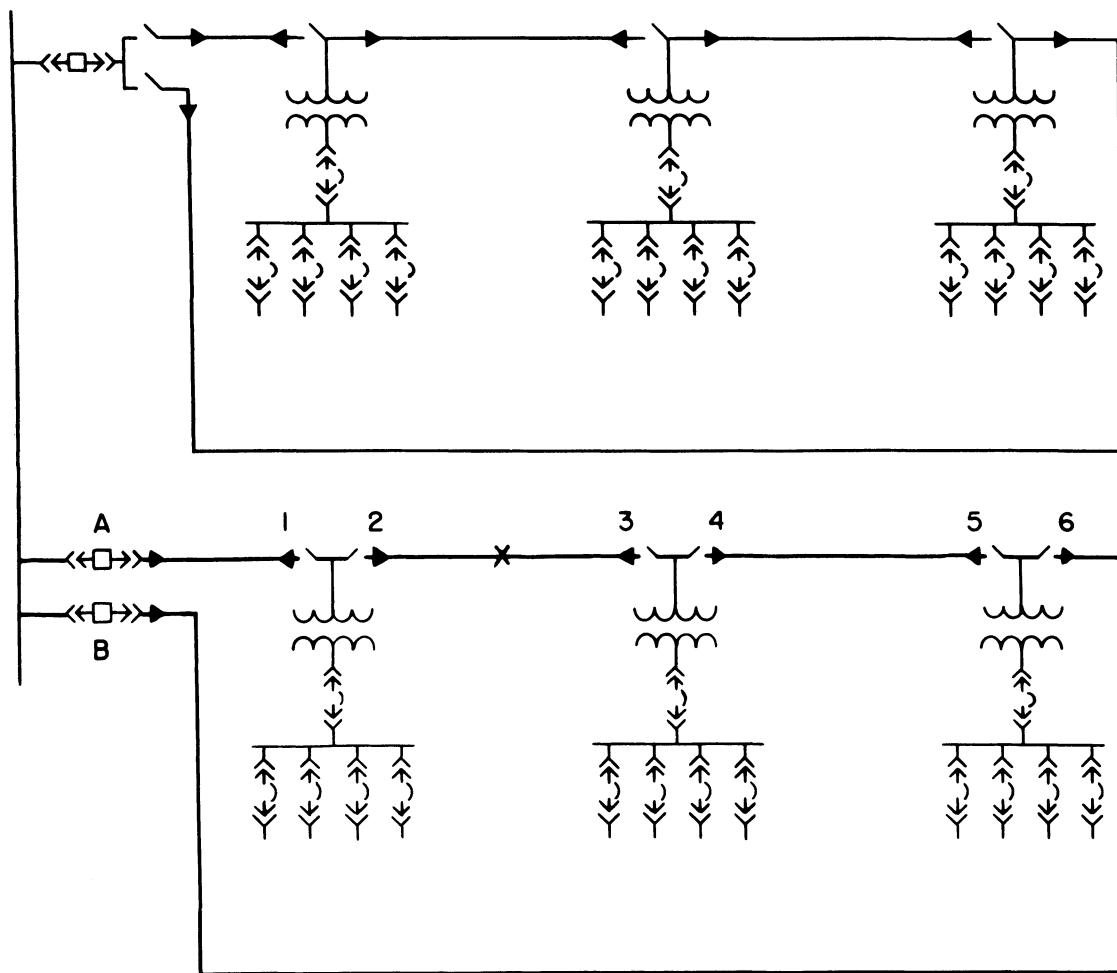


Figure 1.11
Looped primary load-center systems with sectionalizing
switches for supplying load-center unit substations

The primary-selective secondary-network arrangement shown in Figure 1.12 is the form of the network system used most frequently in industrial plants.

This system differs from the radial, secondary-selective, primary-selective and looped-primary system arrangements in several important aspects. The major difference is that a primary feeder or transformer fault will not cause even a momentary interruption of power to any of the loads. The transformer secondaries are interconnected and operated in parallel and two or more primary-feeder circuits are used to supply the system. In effect, there are several parallel paths of power supply from any load on the secondary back to the power source. In many industrial secondary network systems plug-in busway is used for the tie circuits between transformer buses.

If two primary feeders are used to supply the primary-selective network system, half of the transformers would normally be connected to each feeder with adjacent transformers on different feeders. In the event of a primary-feeder fault, the fault is isolated from the system by the automatic tripping of the primary-feeder circuit breaker and all of the network protectors associated with the

faulted circuit. Following these tripping operations, the entire load is supplied over the remaining feeder and half of the network transformers. All transformers can be restored to service by manually switching the de-energized units to the remaining feeder. When the faulted circuit is repaired and the appropriate transformers have been reconnected to the feeder, the network protectors associated with those transformers will close automatically when the feeder breaker is closed.

The network protector is the device that makes it possible to operate the two primary feeder circuits in parallel. The network protector consists basically of an electrically-operated air circuit breaker that is controlled by a directional-power relay and by a phasing-voltage relay. When a primary-feeder fault occurs, there is a flow of power from the secondary to the fault through all of the network protectors associated with the faulted feeder. The directional-power relay in each of these network protectors operates and trips the appropriate network protectors to isolate the fault from the secondary. In the meantime, the primary-feeder breaker has tripped to completely isolate the fault from the rest of the system. When the fault is eliminated, and voltage is restored on the feeder by closing

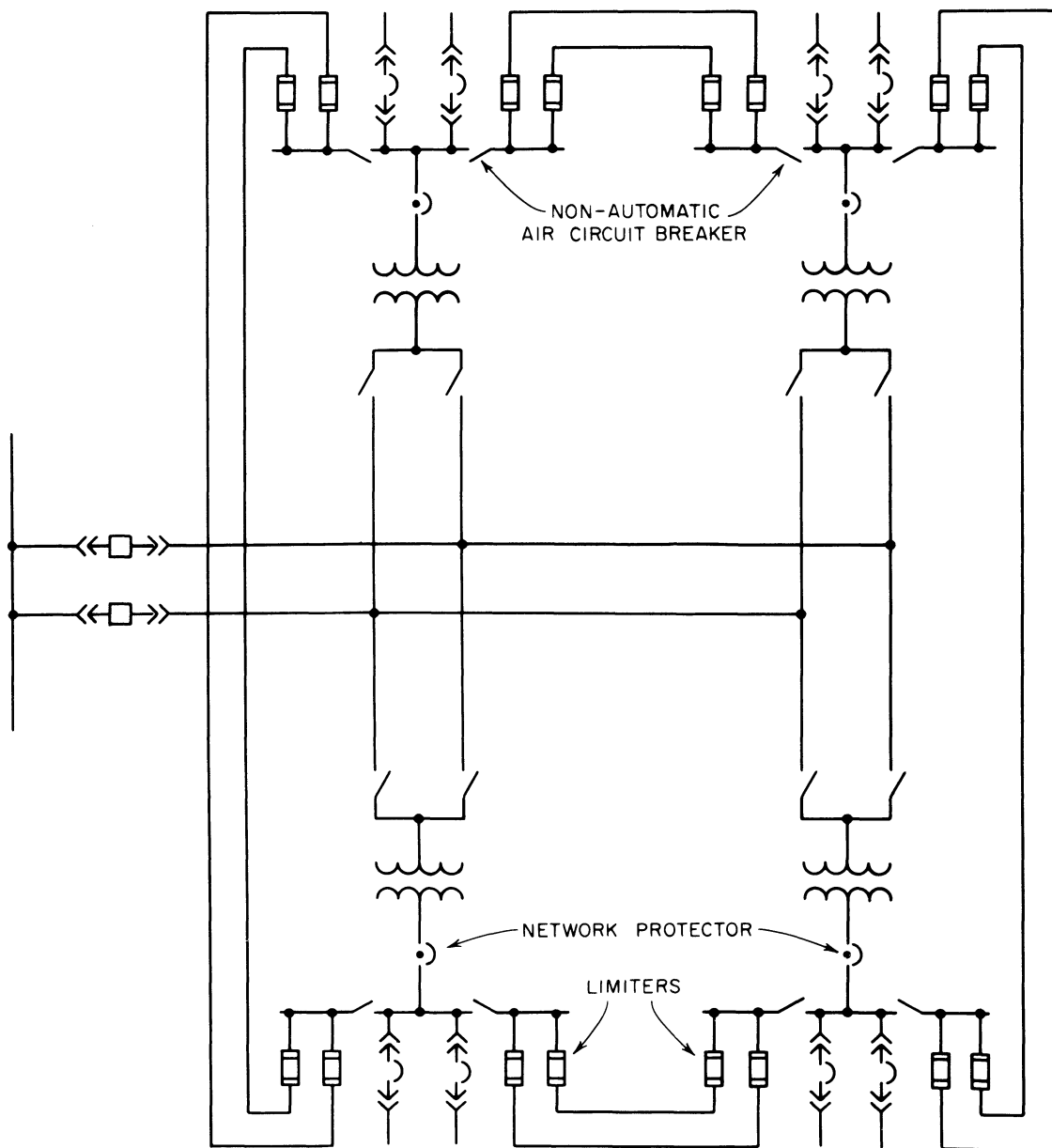


Figure 1.12
Typical primary-selective secondary network
arrangement of load-center distribution system

the feeder breaker, the network relays on all associated network protectors will cause the protectors to close automatically if conditions are such that power will flow from the primary to the secondary.

In addition to providing a high degree of continuity of service to the loads, the network system with its interconnected secondaries inherently offers flexibility to meet shifting or growing loads. In the radial, secondary-selective, primary-selective, and looped-primary arrangements, the magnitude and characteristics of the loads to be supplied from a given transformer secondary bus are governed by the rating of the particular transformer. In the network system, the tie-circuits between transformers make it possible for adjacent transformers to share load

and thereby permit loads on some buses that are in excess of the kva rating of the transformer at that bus. The amount of power that can be transferred between transformer buses will be determined by the tie-circuit impedance, the transformer impedance, and the characteristics of the load.

Spot Network

The secondary-network arrangement described above is designed to serve loads that are reasonably distributed within an area. However, if there are concentrations of critical loads that are widely separated and there is very little load in the areas between them, the spot-network arrangement will be more economical than the conven-

tional network arrangement. The spot-network arrangement operates on the same principle as the conventional network, the main difference is that the transformers are all connected to the same bus.

Figure 1.13 shows two forms of the spot-network arrangement.

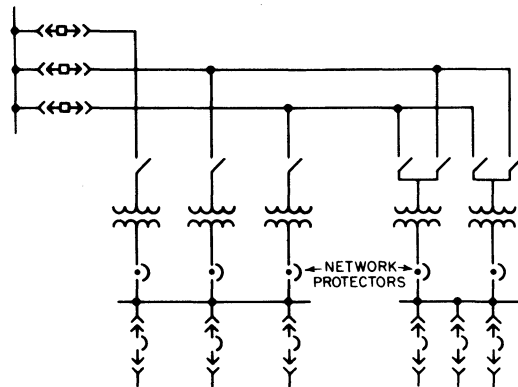


Figure 1.13
Two forms of the spot-network arrangement of the load-center distribution system

SELECTION OF SUBSTATION RATINGS

This discussion assumes that the system circuit arrangement and substation voltage ratings have been decided. The selection of the kva rating of the substation is then largely a matter of economics with the lowest over-all system cost as an objective.

Three major system components affect the over-all system cost. These are primary cable, substations and secondary cable. These factors work contrary to one another so the most economical system as affected by substation kva rating can only be obtained by looking at all three at once.

As the number of substations increases in a given area, the length of primary feeder cable required to serve these substations increases. Conversely, as the number of substations in a given area increases, the amount of secondary feeder cable required decreases. The substation cost per kva varies depending upon the kva rating of the substation. If these factors are combined in their proper proportions for a typical industrial plant, the results will be as shown in Figure 1.14:

The curves in Figure 1.14 indicate that there is a very definite minimum system cost as a function of substation size for different voltage levels. There are also other factors which have an influence on substation rating. The most important of these are:

1. Higher primary voltages may require substations with larger kVA ratings so that a greater kVA per primary feeder can be handled without unduly complicating the substation overcurrent protection problem. For example, when the primary voltage is 13.8 kV, it is desirable to have a loading of 4000 to 7500 kVA per primary feeder. With total primary feeder loadings of this magnitude and using stand-

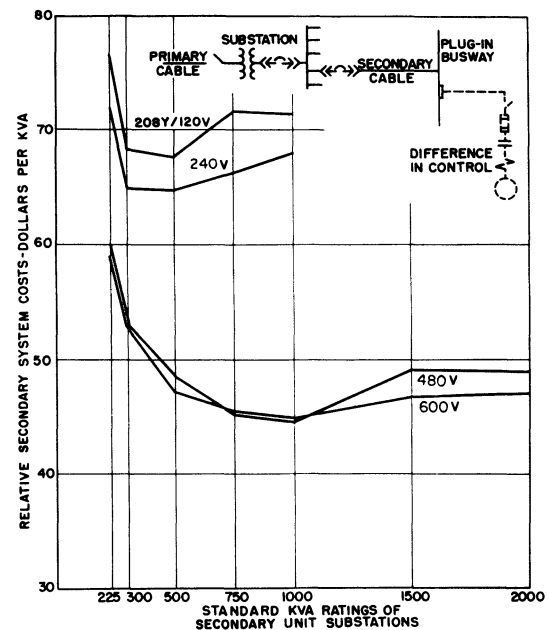


Figure 1.14
Curve showing the approximate installed costs of 208-, 240-, 480-, and 600-volt radial secondary systems

ard 500-kVA substations with typical diversity factors, individual primary overcurrent protection would be required. (National Electrical Code, 1968 edition, article 450-3.) If 750-, 1000- or 1500-kVA substations were selected, then primary feeder loadings of this same order of magnitude could be obtained without individual overcurrent protection. This point is of particular importance in systems with primary voltages of 15 kV and above.

2. Large spot loads can sometimes justify larger unit substations. For example, a single furnace, a single large oven, or a single large welder may justify substations of the order of 2000 to 2500 kVA at 480 volts secondary since there is no secondary distribution. Therefore, there is nothing to be saved in that part of the system to offset the lower cost per kVA of the larger substation with a very few secondary breakers attached to it. Where these larger spot loads are encountered, it is well to consider using two smaller substations rather than one larger substation, particularly if the number of feeder breakers for the secondary exceeds three or four. For general factory areas, two 1000-kVA unit substations will nearly always provide a lower over-all system cost than one 2000-kVA substation. Many times a system using two 750-kVA substations will be less expensive for over-all than a system using one 1500-kVA substation per load area.
3. Space available for unit substations sometimes dictates larger substation kVA ratings. For example, one 1500-kVA substation instead of two 750-kVA substations may be necessary because the space can be found for the one larger unit whereas it could not be found for the two smaller units. Conversely, other areas may allow space for the two smaller units, but not for the larger one.

There are other local factors which may affect the kVA size of substations in a particular plant. In general, however, the points listed on the preceding pages are the major factors involved in the selection of substation sizes for most industrial plants.

LIGHTING DISTRIBUTION METHODS

During the past few years, adequate lighting for factory floor areas has been recognized as necessary for better production and safety. At the present time, illumination levels of 50 lumens per square foot are considered good practice and levels as high as 100 lumens per square foot are not out of the ordinary. Thus, the lighting load in an industrial plant has become an appreciable part of the total load. Load intensities of two to four volt-amperes per square foot for lighting and eight to ten volt-amperes per square foot for power are about normal.

Until the advent of the fluorescent lamp, most distribution of power for lighting loads was at 120 volts for the most efficient operation of incandescent lamps. Higher-voltage incandescent lamps are fragile and generally not very satisfactory. Modern lighting practice, however, includes more and more the use of fluorescent lamps either alone or in combination with other types. Since the fluorescent lamp has a ballast in series with it, the 120-volt limitation no longer applies. The required voltage for starting is always above 120 volts and is supplied by a transformer built into the ballast. The use of fluorescent lamps, therefore, has opened new possibilities for the use of higher voltage circuits to reduce the cost of the power system. And, the trend toward locating the substation at the utilization point has made possible the use of 480Y/277-volt combined light and power systems.

Two points which should be mentioned in connection with using higher voltage fluorescent lighting are as follows. First of all, many plants have high bay areas where mercury and incandescent lamps are often used in combination. The mercury lamps have ballasts like the fluorescent lamps and are, therefore, suitable to higher voltage. The 120-volt incandescent lamps can be operated through small step-down transformers connected to the 480-volt system.

The second point concerns factory office lighting. Frequently, industrial plants are designed with a sizable office area at one end of the factory area. A 480Y/277-volt system can be used for general area fluorescent lighting within the office area. One or more feeders would be run into the office area for general lighting. Whereas, controllers might be used as switching devices in the factory area, either 24-volt remote control relays or 277-volt wall switches may be used in the office area. The relay contacts operate in the 480Y/277-volt system, but the relay coil is supplied with 24 volts from the small transformer. Thus, only 24 volts is within reach of an operator. The 277-volt wall switch can be used in place of the remote control system providing this type of switch can be applied to meet local Codes.

OVERCURRENT PROTECTION

Overcurrent protection assists in preventing or limiting equipment damage, loss of production, building damage

from fire, and injury to personnel. Current is a practical circuit characteristic for actuating a protective system, and overcurrent protection is used in all distribution systems. There are various additional kinds of protection used, such as frequency, differential, under or over voltage or power, but overcurrent protection will normally be employed as back-up protection even where it is not the primary circuit or equipment protection.

It is desirable for the overcurrent protective device to be actuated by moderate abnormal current, as well as higher short-circuit current. Protection is then afforded against equipment damage from overloading, such as for motors or conductors where there has been no dielectric breakdown. However, there are exceptions and a good example where such thermal equipment protection is not obtained is the usual overcurrent protection applied to transformers at levels of about 1.5 to perhaps 6 times rated current.

The kinds of devices used for overcurrent protection are fuses, circuit breakers with direct-acting trips, and circuit breakers or contactors with relays. Fuses must be selected in ratings that will achieve protection objectives; some direct-acting trips are similarly not adjustable. Most relays are adjustable over a wide range and particular protection requirements may be met by adjustment and selection of appropriate current transformer ratings. The protection afforded may be further adapted to special requirements because there will often be a choice in the time-current characteristics of the protective devices available.

In order to maintain maximum electric service reliability, only those circuit protective devices directly associated with a failure or abnormal conditions should function to open the circuit; this is called "selectivity." Selectivity is accomplished by coordination of the various circuit protective devices, commonly on a time-current basis. The type of power system and the characteristics of the various protective devices are both important in achieving selectivity. In general, the simpler the protective system the greater the system reliability.

It is good engineering practice to provide "back-up" overcurrent protection as a safeguard against failure of the primary protection to operate. It may simply provide a second chance to correct an abnormal current condition in a given part of a system or it may supplement the primary protection in another part of the system further removed from the source.

Proper circuit protection should be included during the planning stage of the electric system. Generally, in large industrial plants this is done by the engineering staff. In small plants or simple power systems adequate protection may be achieved by compliance with the National Electrical Code.

It is important to recognize that changes in the electric system, such as increased power or additional loads, may require the resetting of protective devices to assure proper protection and selectivity.

Some types of loads or circuits may have specific requirements. Many of these, including motors, conductors, or transformers, are covered by general rules in the National Electrical Code. Chapter III, on System Pro-

tection, covers many specific suggestions concerning selection, application, and setting of relays.

SPECIAL SYSTEMS

In addition to the problems of general power distribution, the modern industrial plant also has the need for some special types of power. These are high-frequency power, direct-current power, electronic equipment power, and critical load power requirements.

General

The general rule to follow when special power supplies are involved is to use the basic principles of load-center distribution. Locate the device supplying the special service as near the center of the load as possible. Many machine tools, requiring high-frequency power for instance, have the converting equipment built right into the machine itself. The direct-current power can be supplied in the form of motor-generators and controls "packaged" in one unit and included with the equipment itself.

A central power supply may prove to be more economical where a number of special loads can be located within a certain area. The cost of the individual power supply units will be higher than the cost of a larger unit to supply all the loads. The cost of maintaining several units is generally higher than maintaining one unit, especially rotating equipment.

One possible disadvantage of a central power supply is the inability to relocate the utilization equipment conveniently. Today, the emphasis in production is for flexibility. In the modern industrial plant very few machines are fixed. Changes in processes and plant layout to take advantage of the latest manufacturing techniques are everyday occurrences in many plant engineering departments. Limiting such moves due to lack of power supply or requesting additional funds to permit such moves to be made in order to provide the necessary power will show lack of planning on the part of the electrical engineer.

High-Frequency Circuits

High-frequency power in industrial plants should be distinguished from the term as used in electronics and communication fields. Frequencies of 120, 180, 360, 420 and 900 hertz (cycles per second) are most commonly used for higher-speed motors. These motors supply the drive for grinding and polishing machines, woodworking and spinning operations and in small portable hand tools.

The trend is for higher and higher speeds in machine tools. New metal discoveries and new metal alloys not only have permitted these higher speeds but actually demand that these speeds be used in order to get the best efficiencies and tool life. Hence the need for higher frequencies than the conventional 60 hertz.

One of the plus values of the use of high-frequency power is that the motors and transformers are smaller in size and lighter in weight. These two factors make the use of 120 and 180 hertz ideal for the operation of small power tools found on assembly lines in the automobile and aircraft industries.

The source of high-frequency power has generally been from frequency converters of the rotating type. Nonrotating types of converters that incorporate electron tubes, transistors, and controlled rectifiers are now generally available.

Where several frequencies are required, various rotary converters can be mounted on a common base and driven by a standard 60-hertz motor. Circuits are then brought to the machine tool and terminated in a plug board. By plugging in the motor in the various receptacles, speed ranges up to 100,000 r/min are obtainable in one motor alone.

High frequency is also used for induction and dielectric heating. The conversion equipment for these is usually built as part of the unit itself. It is necessary, due to the high impedance, to give special consideration to the circuits between the high-frequency converter and the load it is supplying.

A new use of high-frequency power is for lighting where fluorescent lamps are used. Such lighting will offer many attractive benefits. Fixtures will be lighter in weight, no ballasts will be needed, heat losses from the ballast will be eliminated, more light output per lamp and controllable lumen output of the whole system by varying the frequency are but a few of the benefits that this new system will offer. High-frequency lighting is already being used successfully in subway cars, trolley buses, aircraft and commercial buildings.

Electronic Equipment

The greater use of electronics in industrial plants has brought up a new problem in power distribution voltage control. The problem has always been troublesome in plant operation, but it is becoming more critical due to the increased load of electronic devices.

The major role of electronics in the industrial plant is for specific applications. Some of these applications are: control to operate with the speed of light, control that is super-sensitive, control for quality or inspection, control for remote installations, and control for extreme accuracy. All of these services call for closely regulated performance which in turn call for a system with a low voltage regulation. The foe of such a voltage supply in plants works in two fields. The first is in the field of voltage spread between maximum and minimum voltages caused by the plant loads on transformers, feeders and incoming power supply from the public utility or plant generating units. The second is the disturbances to the voltage supply due to the starting of large motors, arc furnaces, welding and similar large loads of power. The effects of excessive voltage regulation are discussed in Chapter II titled Voltage Considerations.

Direct-Current Power Systems

The use of direct current as power in industrial plants has been increasing. In the early days, plant power was generated by direct-current generators at 250 volts. With the coming of alternating-current power and its many advantages of transmission, most plant equipment was converted to alternating current. However, one of the

most attractive features of direct-current motors was lost in this conversion; this was speed control. Many attempts have been made to obtain this feature with alternating-current motors, but to date it has not been possible to develop an alternating-current adjustable-speed drive which is comparable in cost and performance with a direct-current drive.

Recently, the ability to control speed accurately has been emphasized, especially with machine tools, conveyors, and process equipment. Machine tools have to cover wide ranges of speeds, accurately adjustable to a given speed in order to take advantage of new processes and the discovery of new materials with which to work. The one type of motor that could meet these specifications was the direct-current motor. The big problem was where to get the direct-current power to drive the motors.

There are three practical sources of direct-current power: (1) generation by prime movers, (2) motor-generator sets, and (3) rectifiers. Methods (2) and (3) are the most commonly used today. There are still engine- or turbine-driven direct-current generators in old plants, but the most economical way is to buy or generate alternating-current power, transmit it to the point of use and then convert it either by generation or rectification at that point.

The use of power rectifiers has increased as the modern way of obtaining direct-current power. These rectifiers range from small control units to large rectifier equipments rated in thousands of kilowatts capacity. Rectifiers may be of the electron tube, mercury pools in tanks, silicon cell, selenium cell, germanium cell, or copper-oxide plate type. All these devices take in alternating-current power at all ranges of voltages from the plant distribution systems and convert it to direct-current power in voltages from 6 to 12 volts for plating, 125 volts for lighting, 250 volts for general motor work, 600 to 750 volts for steel mill drives and up to 850 volts for the electrochemical processes.

Rectifiers are attractive from the standpoint of maintenance. They have few moving parts to wear out and the units can be located directly in the manufacturing areas.

Other sources of direct-current power are the "packaged drives." These drives are in one enclosure containing: motor-generator sets, magnetic control, and possibly signal generators and electronic controls. The units are compact and usually can be mounted close to the machine. A number of manufacturers make these units, and they cover all ranges of applications.

SAFETY AND PLANT PROTECTION

General

Protection of personnel and equipment must always be a primary thought in the mind of the electrical engineer when designing any equipment or installation. He must be aware of the many hazards that are present and take adequate precaution to protect against them. It is only by the recognition of these hazards and careful planning to control them that the use of electricity has become the safe and effective means of power transmission that we know today.

Plant protection rests to a large extent upon the shoulders of the electrical engineer for it is he who must provide the plans for adequate alarm systems, communications, emergency lighting and other essential emergency services as well as the general distribution system for normal plant operation.

Personnel Safety

There are listed below items which should be considered in order to provide safe working conditions for the personnel.

1. Interrupting devices should be able to function safely and properly under the most severe duty to which they may be exposed.
2. Protection should be provided against accidental contact with energized conductors by elevation, barriers, enclosures, and other similar equipment.
3. Disconnecting switches should not be operated while they are carrying current, unless designed to do so. Suitable barriers should be provided between phases to confine accidental arcs unless adequate space separation is provided.
4. In many instances interlocks between the disconnecting switch and the power circuit breaker are desirable, so that the breaker in series must be opened first before the disconnects can be operated, thus preventing accidental opening of the disconnects under load.
5. Sufficient unobstructed room in any area containing electric apparatus must be provided for the operator to perform all necessary operations safely.
6. A sufficient number of exits with "panic-type" door features should be provided from any room containing electric apparatus such as a substation, control room or motor room so that escape from this area can be easily effected in the event of failure of apparatus in the room.
7. A protective tagging procedure should be set up to give positive protection to men working on equipment. Such a procedure should be coordinated with the local utility for the common equipment.
8. Industrial plant electric systems should generally be designed so that all necessary work on circuits and equipment can be accomplished with the particular circuits and equipment de-energized. The system design should provide for locking out circuits or equipment for maintenance. Lockout switches should accept three or more padlocks and should be located near the driven equipment convenient for mechanical maintenance personnel so that non-electrical personnel need not enter motor and control rooms. The lockout device should be carefully identified with its associated driven equipment. In very special situations where it is necessary to work on energized circuits, specially trained crews with adequate safety equipment should be used.

9. Rubber gloves deteriorate and consequently should be checked regularly, otherwise they may become more of a hazard than a safeguard because they give the operator a false sense of security. In general, they should not be used without leather protectors if the work is such that the glove may be snagged or torn.
10. All circuits should be marked in the switching station so as to be readily identified. Cables should be identified with suitable tags at both ends and in all manholes for the protection of men working on them.
11. Consider the fire and explosion hazard of oil-filled apparatus and whether such equipment is permitted by Codes. Wherever possible, substitute apparatus such as air circuit breakers, air load-interrupter switches, and askarel-insulated or dry type transformers.
12. A fire brigade should be formed of local employees who are familiar with the equipment and the hazards involved. This group should be trained in the proper procedures to follow in the event of fire in the electric apparatus, the proper use of the various types of extinguishers and methods of fire fighting.

Medium-Voltage Installations

The use of load-center distribution systems in industrial plants involves the installation of wiring and equipment operated between 2.4-kV and 14.4-kV. The design and installation of these systems must take into account the qualifications of the personnel who will be called upon to operate and maintain them. Plant personnel assigned to operate and maintain equipment energized at voltages above 600 volts must be trained in proper operating procedures and impressed with the hazards involved.

Equipment installed in areas that are accessible to other than qualified personnel should be completely enclosed so that no live parts are exposed or readily accessible. Where live parts are exposed or where safe practice dictates, equipment should be installed in locked equipment rooms or fenced enclosures and the distribution of access keys should be limited to qualified persons. Appropriate signs should be used to identify the equipment and provide operating instructions.

Wiring diagrams of the system must be available to operating and maintenance personnel together with the type, make, and ratings of equipment and relay settings. When fuses are used in a system, a stock of spare fuses of the appropriate ratings should be maintained. These practices are particularly important in cases where contract electricians who are not familiar with the system or equipment are called in to perform maintenance or repair work.

Plant Communication and Alarm Systems

Any plan for the protection of a plant must include an adequate and reliable system of communication, both within the plant and to the associated utilities and emergency services which may be called upon in case of need. This can be accomplished in several ways; a principal

one is by a completely self-contained and self-maintained inter-plant system of telephones, alarms, etc., and may include modern radio equipment. Another plan consists of a joint system tied in to the existing communication services.

Fire alarm circuits, whether self-contained or tied into city alarm systems, should be installed in a manner that will guarantee the least interruption from faults and changes in buildings or plant operations. Lines should be arranged to provide easy means of testing and of isolating portions of the system, in case of fault or changes, without interference with the balance of the system.

Watchman circuits are used in many plants for the purpose of providing a ready means for the individual watchman to report unusual circumstances to his supervisor without delay. Such systems are frequently combined with loudspeaker paging systems and/or other alarm methods. The use of annunciators in groups located at central points provides a means of recording calls and actuating other devices. Their use is proving to be a great aid to the engineer charged with a plant communication system installation.

In the larger plants of the country today, there are to be found many installations of short-wave radio communications which offer many advantages, especially instant communication with mobile units. Others have installed systems which are connected to existing plant distribution systems and by impressing a modulated high-frequency carrier wave are able to transmit voice over the existing power circuits.

No matter what type of system is used, care must be taken to see that it is effectively laid out to give the coverage required, that it is installed in a practical safe manner, free of external faults, and that it is supplied with power at all times.

Protective Lighting

No plant protection system is complete unless it has ample provision for lighting vulnerable areas, where employees enter and leave the plant, fences and boundaries and other particularly important points. Lighting of these areas is usually arranged to be independent of normal lighting circuits and may be used either continuously during the night hours or may be controlled for intermittent use automatically or by the plant protection personnel. Critical areas may be protected by providing ample lights to illuminate the area either by local fixtures or by flood-lighting from more distant points, but sufficient units must be used to provide complete coverage.

Boundary lighting is often found to provide more useful illumination when asymmetrical fixtures are used and arranged so that the greater portion of the light output is spread along the boundary.

The general aspects and much detailed information on industrial wiring methods may be found in the IEEE Standards Publication No. 241, "Electric Systems for Commercial Buildings", and the reader is referred to that book for more details of lighting problems.

Emergency Power

Emergency lights should be provided where necessary to protect personnel against a sudden failure of lighting. Areas to be especially considered are those where people congregate and where controls for processes are located, particularly when the controlled functions are supplied from different sources of power than that supplying the lighting.

The National Electrical Code requires that any building or part of a building designed or intended or used for dramatic, operatic, motion picture or other shows shall be provided with an emergency lighting system if the seating capacity of the auditorium exceeds 100 persons. The National Fire Protection Association's Building Exits Code also outlines the requirements for emergency lighting of exits in various classes of buildings used for public assembly, including factories. It requires that the electric power used for emergency lighting purposes shall be supplied from a source independent of that for the general lighting or shall be controlled by an automatic device which will operate reliably to switch the circuit to an independent secondary source in the event of failure of the primary source of power.

Emergency power systems may also be desirable to insure continuity of service in certain processes or occupancies where loss of power may introduce a fire or explosion hazard or result in extensive damage to materials being processed. These emergency systems should be installed in accordance with the rules and regulations of the National Electrical Code and may have as a source a separate service connection with the utility power system, a storage battery, or an engine-driven generator.

CODES General

Safety to life and the protection of property from electric arcing, fire and explosions which may result from the installation and use of electric equipment should be carefully considered during the design stages of a proposed electric installation. State and municipal regulations will vary to some extent and fire and casualty insurance carriers usually have definite requirements for the safeguarding of specific hazards associated with the use of electric apparatus. Details of the proposed installation should be reviewed with representatives of these various groups before construction is started. In some cases there are no local regulations or ordinances and the only authorities having any jurisdiction are the insurance carriers.

In general all electrical construction should conform to the latest requirements of the National Electrical Code and the National Electrical Safety Code. Both of these publications are USA Standards and approved by the United States of America Standards Institute. The National Electrical Code is published by the National Fire Protection Association (NFPA). They are generally accepted by most state, municipal and insurance authorities as the minimum requirements considered necessary for safety, although careful check should always be made with any municipal authorities who may have jurisdiction as

these standards are sometimes modified or amplified by them to conform with local conditions.

In Canada the counterpart of the National Electrical Code is the Canadian Electrical Code Part I published by the Canadian Standards Association.

Codes as Applied to Property Protection

A potential fire or explosion hazard is inherent with the use of nearly all electric apparatus and proper arrangement and protection of the equipment at the start will minimize if not eliminate serious property damage or interruption to production when insulation failures or breakdowns occur.

The fire and explosion hazard of oil-insulated and compound-filled equipment is one of the most common hazards to safeguard against. Fires or explosions in oil insulated transformers occur infrequently, but where they do the results may be disastrous depending upon the arrangement of the equipment and the safeguards provided. The old practice of locating oil-filled transformers in the same room with an important switchboard or switchgear or other valuable apparatus should be avoided because a fire in the transformer will usually involve the other equipment increasing the damage and prolonging the interruption to production.

The National Electrical Code clearly outlines the installation requirements for transformers of all types. Oil-insulated transformers installed indoors must be installed in a vault of fire-resistant construction if the total capacity exceeds 75 kVA. Where a vault is required, adequate ventilation and drainage facilities are necessary to prevent overheating of the transformer and to drain away, to a safe place, any oil that may be released or expelled.

The cost of a vault may be eliminated, and a saving in space effected, by substituting askarel-insulated or dry type transformers in place of the oil-insulated type. Dry-type sealed-tank nitrogen-filled transformers are considered fire and explosion resistant and need no special safeguards from this standpoint.

Where oil-insulated transformers are installed outdoors they should be located at least 25 feet away from combustible buildings or structures. They should not be located under important bridges, conveyors, tanks or similar structures where heat from a fire in the transformer may cause collapse of or serious damage to the structure. Facilities such as crushed stone-filled basins or drained concrete basins should be provided under the transformers to drain away any oil that may be expelled from them in time of trouble. Where a fire in one outdoor oil-insulated transformer is likely to involve other transformers in the same bank, a non-combustible barrier or wall is sometimes provided between adjacent transformers to confine the fire to the unit in which it started.

Permanently piped fire extinguishing systems may also be installed over large oil-insulated transformers or other oil-insulated apparatus where the value or importance of the apparatus and nearby equipment justifies this expense. These systems may be arranged to discharge either manually or automatically. One system employs water spray nozzles connected to a reliable and strong water supply

arranged to completely envelop the transformer with a dense fine spray if fire occurs. The effectiveness of this system depends upon many factors such as the size of nozzles, nozzle spacing, elevation, direction and angle of discharge, water pressure, wind velocity and temperature of the oil. Carbon dioxide is also available as an extinguishing medium in these fixed fire extinguishing systems for both indoor and outdoor installations.

Electric arc furnace transformers are frequently installed in the same vault with the oil circuit breaker controlling the transformer and the control panel for raising and lowering the electrodes. This is not considered a good arrangement as failure of either the transformer (which is usually the oil-insulated type) or the circuit breaker will sometimes involve the other equipment in the vault resulting in increased property damage and an extended interruption to production. A preferred arrangement is to place the transformer, the circuit breaker and the control panels, each in its own vault. The circuit breaker, which is subjected to severe duty, should be very carefully maintained. Air circuit breakers are generally used for arc-furnace duty.

The oil used in the lubricating and governor systems of steam-turbine driven generators is a potential hazard where the steam temperatures are 700°F or higher. Turbine oil will ignite if it contacts hot steam lines of this temperature. It is important, therefore, to arrange the oil lines so that if leaks should develop the oil will not drip or be sprayed on hot metal parts. Thermometers and other similar accessories on these systems should be protected against breakage.

Large enclosed generators, excepting the hydrogen-cooled type, should be provided with a built-in type of fire-extinguishing system. Failures do occur in these machines from both electrical and mechanical causes, as well as lightning, and considerable additional damage often results from the ensuing fire. In enclosed machines such fires are inaccessible and the built-in fire protection is the only possible way of extinguishing a fire, if it occurs, and keeping the damage to a minimum. The two common means of extinguishing fires in such machines which are now employed are:

1. The perforated spray rings installed in the end bells at each end of the machine, arranged to discharge water over the end turns upon manual operation of a conveniently located control valve, and;
2. The use of carbon dioxide arranged to discharge automatically or manually from a battery of cylinders into the interior of the generator. These systems are designed to maintain a sufficient concentration of gas during the decelerating period to completely extinguish any fire in the machine.

Hydrogen-cooled generators need no built-in extinguishing equipment since a purity of about 97 percent of hydrogen is normally maintained in the machine and ignition cannot take place under these conditions.

Large, enclosed, valuable motors, such as the reversing mill motors in steel mills, should also be provided with a built-in fire extinguishing system to help minimize the

damage if fire occurs. On smaller enclosed motors under 3000 horsepower, the expense of a built-in fire extinguishing system may not be justified, but in any case covered openings should be provided in the enclosure to permit the easy application of extinguishing agents to the windings in case of fire.

The grouping together of a number of valuable or important cables or wires in trenches, cable boxes, junction boxes and manholes should be avoided, particularly if they have combustible insulation. This applies to both low, medium, and high-voltage installations, and lead-sheathed cables as well. A failure in one cable or conductor can cause an arc that ignites the insulation on one cable and fire may destroy the entire group, or the arc can do extensive damage in the event of sustained arcing. Where it is necessary to group such cables together, they should be protected with a fireproof covering. The control circuits in power houses and substations should be arranged so that they will not be exposed to damage by arcing or fire. When possible, these wires should have asbestos or similar fire-resistive coverings.

An adequate supply of fire extinguishers should be provided on the premises, particularly in the vicinity of large quantities of electric apparatus. Extinguishers suitable for use on live electric apparatus are the vaporizing liquid, carbon dioxide, and dry chemical types. Where insulating oil or compound is present in large quantities in power houses, substations, and motor rooms where there are many large motors present, small hose (1½ inch) protection with portable spray nozzles should be provided as back-up protection in the event that the hand extinguishers are inadequate.

Soda acid and foam type extinguishers are dangerous to use on live electric apparatus because the materials used are conducting. Care should also be exercised when using carbon tetrachloride extinguishers on a fire in a confined space as the fumes are toxic.

GROUNDING

The subject of grounding may be divided into two main parts. That is, the grounding of the system for electrical operating reasons and the grounding of non-current-carrying metal parts for safety to personnel.

The principal reasons for grounding an electric system are:

1. Reduce operating and maintenance expense.
2. Keep transient overvoltages that may appear on a system at a minimum.
3. Improve service reliability.
4. Limit the displacement of the neutral for greater safety.
5. Better system and equipment overcurrent protection.
6. Readily locate and isolate circuits which have become accidentally grounded.
7. Improve lightning protection.

The grounding of electric systems and equipment has been a National Electrical Code requirement for many years. This Code states specifically that "Circuits are grounded for the purpose of limiting the voltages upon the circuit which might otherwise occur through exposure to lightning or other voltages higher than that for which the circuit is designed; or to limit the maximum potential to ground due to normal voltage." The latest requirements for grounding low-voltage systems may be found in Article 250 of the 1968 Edition of the National Electrical Code.

Failure to provide proper grounding for electric equipment may be considered as the primary cause of many accidents which have resulted in the death of personnel and no system is complete unless adequate grounding connections have been made. This subject has been covered in Chapter V of this book in detail, but because it is such an important phase of the electric installation, it must not be passed over too lightly. This is particularly important when we realize that high voltages are not necessary to cause death from electric shock. Many deaths are recorded annually resulting from shock received from the usual 115-120 volt lighting and appliance circuits and many of these could and should have been avoided by proper grounding procedures.

MAINTENANCE

The design of equipment and the design of equipment installations should provide for adequate protection to the electric parts from oils, greases and dirt, all of which are generally very harmful to the windings and insulation. As heat is a common enemy of most electric equipment, a proper ventilating method must be provided both in the equipment design and in the installation.

Dirt is probably the greatest enemy of all electric equipment because the accumulation of dirt and dust affects the equipment's internal and external ventilation. This results in greater heating of parts with the resulting lowered efficiency and therefore progressively increased heating. At the same time this shortens the life of the insulation because most insulating materials have a life expectancy which decreases rapidly when the temperature rises.

Rotating equipment requires lubrication and where lubrication is needed, wear usually is found. Bearings must be checked to maintain proper clearances between the stationary and rotating parts.

Insulation of equipment usually depreciates with age. Careful checks on the decrease of insulation resistance prevents many failures. A sudden drop in insulation resistance of any unit is indicative of developing trouble and this can frequently be forestalled by immediate corrective measures.

Protective devices will function properly only if regularly examined and checked. An overload relay which does not open a circuit at the designed level of operation is poor insurance against preventing serious electrical failure. Systems have even been reported where overload relays were actually blocked out of service to prevent their tripping. Details of system relaying are given in Chapter III.

The essence of good maintenance can be summarized as follows:

1. Cleanliness. Keep equipment clean and well ventilated.
2. Regular inspections. Note variations from normal conditions.
3. Lubrication. Apply proper lubricants when needed. Develop lubrication schedules and adhere to them.
4. Repairs and adjustments. Remember that small repairs or adjustments that are neglected or postponed too long frequently lead to more extensive repair jobs.
5. Records. Develop a system of record keeping which will show the repairs required by the equipment over a long period.

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CHAPTER II

VOLTAGE CONSIDERATIONS

NOMINAL SYSTEM VOLTAGES AND EQUIPMENT VOLTAGE RATINGS

Before starting a discussion on system voltage problems, it is necessary to have an understanding of the system voltage nomenclature and the preferred voltage ratings of various apparatus used in the system so that the proper voltage identification can be used throughout. It is also necessary to know why the voltage designations are applied to help in understanding the system voltage discussion in the following sections.

PROGRESS WITH SYSTEM VOLTAGE NOMENCLATURE

The IEEE Industrial and Commercial Power Systems Committee has had a long interest in the nomenclature for alternating-current power systems as applied in industrial plants and commercial buildings. A very comprehensive and significant paper, the "Report on Industrial Voltage Requirements,"¹ was presented at the 1947 AIEE Summer General Meeting by the then Subcommittee on Industrial Voltage Requirements. (The "Report on Industrial Voltage Requirements," Transactions Paper 47-157, was published in the April 1948 issue of *Electrical Engineering*.)¹ In 1958 a System Voltage Nomenclature Working Group of the Codes and Standards Subcommittee of the AIEE Industrial and Commercial Power Systems Committee was formed and later produced the paper, "A-C System Voltage Nomenclature for Industrial and Commercial Power Systems,"² presented in October at the 1960 Fall General Meeting. Upon the recommendation of the Industrial and Commercial Power Systems Committee, it was submitted to the Standards Committee of the Institute with the result that it became Standards Publication No. 92, published in December 1962.

The formal acceptance of IEEE No. 92 (formerly AIEE No. 92) documented a comprehensive approach to the areas needed to change the national standard on this subject. In fact, the closing paragraph states that "it is a further recommendation of this Committee that the proposed voltage ratings and practices included in the paper be submitted to the American Standards Association to be adopted in their Standard on 'Preferred Voltage Ratings for A-C Systems and Equipment'."³

The System Voltage Nomenclature Working Group had a specific motivation in wanting to develop a consistent and workable voltage Standard. That desire concerned the work then underway by the Committee to develop consistent voltage terminology in the Committee's present publications. During this time the third edition of *Electric Power Distribution for Industrial Plants*⁴ (known as the Red Book) and *Electric Systems for Com-*

*mercial Buildings*⁵ (known as the Gray Book) were in preparation. Chapter II of the Red Book, titled "Voltage Considerations," and Chapter III of the Gray Book, titled "Voltage Selection," are both based on the system voltage nomenclature practices developed in the Working Group paper.

A Look at C84

The present Standard for the rating of all alternating-current systems and equipment in the United States is *Preferred Voltage Ratings for AC Systems and Equipment*, USAS C84.1. (The American Standards Association became the United States of America Standards Institute in September 1966.) This Standard is based on the report of a joint committee of the Edison Electric Institute (EEI Publication R-6) and the National Electrical Manufacturers Association (NEMA Publication 117) published in May 1954; this revised the Standard issued in 1930.

The present Standard C84 detailed the voltage zones into the categories of *favorable zone* and *tolerable zone*. The present voltage-band limits for these zones are given in Table 2.1, which is a copy of C84. To develop an understanding of the meaning of these zones, the definitions of both the favorable and tolerable zones from C84 are as follows.

Favorable Zone

"This zone will contain the greater part of the existing voltages. Systems will ordinarily be designed with the intention that most of their operation voltages lie within this zone. Equipment will ordinarily be designed and rated so as to give fully adequate and efficient operation throughout this zone, although not necessarily with normal characteristics at all voltages."

Tolerable Zone

"This zone will contain voltages which lie above and below the Favorable Zone. These necessarily result from practical operation under field conditions. They must be recognized as a normal part of the existing range of voltages, although not those most desirable. Systems will ordinarily be designed so that the frequency of occurrence of such voltages, both as to location and as to time, will be minimized. Equipment should, in general, be able to give fairly satisfactory operation throughout this zone, although not necessarily with as good characteristics as are given through the Favorable Zone. For some types of equipment, modification of loading or even alternate designs may be required for satisfactory operation in the upper and lower parts of the Tolerable Zone."

Table 2.1
System Voltages

System Designation in Terms of Base Voltage (BV)	Preferred Base Voltage	Preferred Nominal System Voltage (a) (g)	Voltage Zones			
			Favorable Zone		Tolerable Zone (d)	
			Minimum	Maximum	Minimum	Maximum
VOLTAGES AT POINT OF UTILIZATION BY EQUIPMENT						
1 BV	120	120	110	125	107	127
1/2 BV	120	120/240	110/220	125/250	107/214	127/254(c)
1/1.73Y BV	120	120/208Y	114/197Y	125/216Y	111/193Y (c)	127/220Y
2 BV	120	240	210	240	200	250
4 BV	120	480	420	480	400	500
5 BV	120	600	525	600	500	625
20 BV	120	2400	2200	2450	2100	2540
20/34.6Y BV	120	2400/4160Y	2200/3810Y	2450/4240Y	2100/3630Y	2540/4400Y
40 BV	120	4800	4400	4900	4200	5080
60 BV	115(b) 120(b)	6900(b) 7200(b)	6300	6900	6000	7200
PRIMARY VOLTAGES AT DISTRIBUTION TRANSFORMERS						
20 BV	120	2400	2300	2500	2200	2600
20/34.6Y BV	120	2400/4160Y	2300/4000Y	2500/4330Y	2200/3810Y	2600/4500Y
40 BV	120	4800	4600	5000	4400	5200
60 BV	120	7200	6900	7500	6600	7800
40/69.3Y BV	120	4800/8320Y	4600/8000Y	5000/8660Y	4400/7620Y	5200/9000Y
100 BV	120	12000	11000	12500	10500	13000
60/103.9Y BV	120	7200/12470Y	6900/12000Y	7500/13000Y	6600/11450Y	7800/13500Y
63.5/110Y BV	120	7620/13200Y	7270/12600Y	7960/13800Y	7000/12100Y	8250/14300Y
110 BV	120	13200	12600	13800	12100	14300
120 BV	120	14400	13000	14500	12600	15000
VOLTAGES AT SUBSTATIONS AND ON TRANSMISSION SYSTEMS						
20 BV	120	2400	2300	2600	2200	2750
20/34.6Y BV	120	2400/4160Y	2300/4000Y	2600/4500Y	2200/3810Y	2750/4760Y
40 BV	120	4800	4600	5200	4400	5500
60 BV	120	7200	6900	7800	6600	8250
40/69.3Y BV	120	4800/8320Y	4600/8000Y	5200/9000Y	4400/7620Y	5500/9520Y
VOLTAGES AT SUBSTATIONS AND ON TRANSMISSION SYSTEMS						
100 BV	120	12000	1100	13000	10500	13200
60/103.9Y BV	120	7200/12470Y	6900/12000Y	7800/13500Y	6600/11450Y	7920/13700Y
63.5/110Y BV	120	7620/13200Y	7270/12600Y	8250/14300Y	7000/12100Y	8320/14500Y
110 BV	120	13200	12600	14300	12100	14500
120 BV	120	14400	13000	15000	12600	15500
200 BV	115	23000	(e)	(e)	20400	25800
240 BV	115	27600	(e)	(e)	24500	31000
300 BV	115	34500	(e)	(e)	30600	38000
400 BV	115	46000	(e)	(e)	40000	48300
600 BV	115	69000	(e)	(e)	60000	72500
1000 BV	115	115000	(e)	(e)	100000	121000
1200 BV	115	138000	(e)	(e)	120000	145000
1400 BV	115	161000	(e)	(e)	140000	169000
2000 BV	115	230000	(e)	(e)	200000	242000
(See Note (f))						

NOTES:

(a) Except for the first and second lines, which indicate the usual single-phase two- or three-wire systems, the figures in the third column refer to three-phase systems.

(b) Since utilization at this level is confined principally to 6600-volt motors in large steel mills, mines, etc., a nominal designation of 6900 volts is commonly used and is included herewith, even though it is not consistent with other nominal voltages in the utilization group. The voltage zones for this level are likewise related to 6900 volts rather than to 7200 volts.

(c) Equipment to be used on both the 120/208Y and the 240-volt systems must recognize the minimum voltage of the former and the maximum voltage of the latter.

(d) Equipment designed for the Favorable Zone will in general give fairly satisfactory operation throughout the Tolerable Zone, except that modification of loading or alternate designs may be required for certain types of equipment.

(e) For systems with nominal voltages above 14400 volts, designation of a "Favorable Zone" has been omitted as being somewhat less necessary than for the lower voltages. It should be considered, however, that the relationships and definitions pertaining to the lower voltages apply equally well to the higher voltages.

(f) Preferred system voltages above 230 kV are not included in this table. A study of these higher voltages is still under way in conjunction with the International Electrotechnical Commission.

(g) In order that other numerical designations for system voltages which are sometimes used may be interpreted in terms of the "Preferred Nominal System Voltages" values shown in Table 2.1, the following* tabulation has been prepared. It should be emphasized that all of the different values on any one line refer to the same system as defined by its zone values in Table 2.1. Apparatus ratings indicated in other tables in this report in connection with the "Preferred Nominal System Voltages" apply, therefore, equally well where these other designations are used.

* See next page for continuation of Note (g)

Note (g) of Table 2.1 continued

<i>Preferred Nominal System Voltage</i>	<i>Other Designations for Identical Systems</i>
120	110, 115 or 125
120/240	110/220 or 115/230
120/208Y	115/199Y
240	220 or 230
480	440 or 460
600	550 or 575
2400	2200, 2300 or 2500
2400/4160Y	3810 or 4000
4800	4400, 4600 or 5000
7200	6600, 6900 or 7500
4800/8320Y	8000
12000	11000 or 11500
7200/12470Y	11450, 11950 or 12000
7620/13200Y	—
13200	13500 or 13800
14400	13200, 13800 or 14000
23000	22000 or 24000
27600	26400
34500	33000 or 36000
46000	44000 or 48000
69000	66000 or 72000
115000	110000 or 120000
138000	132000
161000	154000
230000	220000

The current activity of the present USA Standards Committee C84 has re-examined the definitions of the two voltage zones and, because of the difficulty of finding a clear and succinct title for the zones, has presently labeled them Range A and Range B. It should be observed that the scope of the proposed definitions needfully differ from the present C84. The current definitions are as follows.

Range A: Service Voltage

"Electric supply systems shall be so designed and operated that most service voltages are within the limits specified for this range. The occurrence of service voltages outside of these limits is to be infrequent with respect to time and place."

Range A: Utilization Voltage

"User systems shall be so designed and operated that, with service voltages within Range A limits, most utilization voltages are within the limits specified for this range."

"Utilization equipment shall be designed and rated to give fully satisfactory performance throughout this range."

Range B: Service and Utilization Voltages

"This range includes voltages above and below Range A limits that necessarily result from practical operating conditions on supply and/or user systems. Although such conditions are a part of practical operations, they shall be limited in extent, frequency and duration. When they occur, corrective measures shall be undertaken within a reasonable period of time to improve voltage to within Range A limits."

"Insofar as practicable, utilization equipment shall be designed to give acceptable performance in the extremes of this range of utilization voltage, although not necessarily as good performance as in Range A."

"It must be recognized that, because of conditions beyond the control of the supplier and/or user, there will be infrequent and limited periods when sustained voltages outside of Range B limits will occur. Utilization equipment may not operate satisfactorily under these conditions, and

protective devices may operate to protect the equipment. When voltages occur outside the limits of Range B, prompt corrective action is recommended. The urgency for such action will depend upon many factors, such as location and nature of load or circuits involved, and magnitude and duration of the deviation beyond Range B limits."

LOW-VOLTAGE SYSTEMS

To correlate the different system voltage levels, the starting point in the industrial field is with low-voltage systems.

Change in Motor Voltage Rating

After ASA C84.1 was issued in 1954, problems continued to appear with the 220- and 440-volt ratings of electric motors. Table 2.2 shows an extract from the Standard listing the maximum and minimum voltages in the *favorable zone* for the 120-, 240-, and 480-volt systems. As quoted earlier, the *favorable zone* is defined as that in which most operating voltages will fall. It should be noted that the 120-volt system allows a 5-volt rise above nominal voltage, but *no* plus tolerance is allowed for the 240- and 480-volt systems.

IEEE Standards Publication No. 92 recognized the disadvantage of retaining the nine percent difference between the 480-volt transformer and 440-volt motor. Actual operating practice indicates that the system voltages were about five percent above the motor voltage. This reduced system-voltage drop was due to the general adoption of the *load-center* principle of distribution. Accordingly, it recommended that the standard NEMA transformer be operated on the plus two and one-half percent tap to give a secondary voltage of 468 volts with rated primary voltage. This approach would eventually lead to the adoption of a line of transformers rated at 460 volts, in place of 480 volts, to be more closely in harmony with the 440-volt motor. This approach was not acceptable to the electric utility industry which has made a long and continuous effort to standardize on transformers based on multiples of 120 volts. Thus, the alternative was to retain the 120-volt based transformer and investigate the possibility of going to a three-phase motor based on multiples of 115 volts as presently exists for low-voltage single-phase systems so as to accomplish the same end result of harmony between the system and motor voltages. Careful study was given to this subject by a joint committee of the NEMA Motor and Generator Committee and the NEMA Industrial Control Committee. A result has been publication of *Suggested Standard for Future Design*.⁶ There has been wide acceptance of the proposal to line up the three-phase motors on the 115-volt base, which has been the basis for single-phase motors for many years.

Problems of Standard Usage

Because of discrepancies in tolerances between utilization equipment and power system voltages, there have been a number of unfair complaints that the utilities were raising the voltage.

Table 2.3 shows an extract from the tabulation of *primary voltages at distribution transformers* for the 12000-volt (not usually an industrial voltage but easy to use by way of comparison) system showing a maximum voltage of 12500 volts and a minimum voltage of 11000 volts for

the *favorable zone*. Table 2.4 shows that if the maximum voltage of 12500 volts is applied to the primary of a standard 12000-volt distribution transformer, the secondary voltage will be 125 volts for a 120-volt transformer, 250 volts for a 240-volt transformer, and 500 volts for a 480-volt transformer. Table 2.2 shows that 125 volts is within the *favorable zone* for the 120-volt system but exceeds the *favorable zone* for the 240- and 480-volt systems. Table 2.5 shows that 125 volts is within the tolerance of the 115-volt motor but 250 volts exceeds the tolerance of the 220-volt motor and 500 volts exceeds the tolerance of the 440-volt motor. As a result there were numerous complaints that the utilities were raising the voltage when the actual cause was the requirements of the Standard and the ratios of the standard transformers built to meet them.

Table 2.2

System Nominal Voltage	Favorable Zone Voltage	
	Minimum	Maximum
120	110	125
240	210	240
480	420	480

Table 2.3

System Nominal Voltage	Favorable Zone Voltage	
	Minimum	Maximum
12000	11000	12500

Table 2.4

Primary Voltage	Secondary Voltages		
12000	120	240	480
12500	125	250	500

Table 2.5

Motor Rating Voltage	115	220	440
10 percent plus	126.5	242	484

Table 2.6

Primary Voltage	Secondary Voltage
12000	208
11000	191

Another problem concerns the use of the 220-volt motor on 208Y/120-volt systems. Originally the 208-volt system was developed to provide an economical and highly reliable system for light and power services in the commercial buildings of large cities. Since the operation of a 220-volt motor with a minimum voltage limit of 198 volts was marginal, the voltage of the standard network transformer was standardized at 216Y/125 volts to provide 208 volts at the customer service. Since network system voltages are relatively stable due to the relatively short primary feeders, satisfactory service is generally secured, especially since most power equipment is installed in the basement close to the power source.

The recent development of commercial installations such as shopping centers, high-rise apartments, motels, and offices brought an increased demand for 208-volt service to supply the large lighting and air-conditioning loads. Standard 208-volt transformers (not the 216-volt network type) were used and supplied from relatively long suburban feeders. The 208-220/440-volt conventional open motor might be in difficulty from low voltage. This is due to the application of standard 208Y/120-volt unit substation transformers (not the 216Y/125-volt network type) and these transformers may be supplied from relatively long suburban feeders. (It should be noted that motors particularly designed for 208 volts or the hermetically sealed type designed for a larger voltage range should still be satisfactory.) As low-voltage problems materially increase, motors develop lower torque and larger losses and may overheat. Table 2.6 contains an extract from the Standard showing that when the voltage of a 12000-volt system drops to 11000 volts, the minimum limit of the *favorable zone*, the secondary voltage will drop to 191 volts, well below the minimum limit of 198 volts for a 220-volt motor.

Industry and Commercial Power Systems Proposal for 230-, 460-, and 575-Volt Systems

In the late 1950s, the System Voltage Nomenclature Working Group reached the conclusion that the 240- and 480-volt systems produced voltages too high for the 220- and 440-volt motors; the solution was to lower the voltages in the low-voltage system to a 115-volt base from the present 120-volt base to produce a low-voltage system in the series 115, 230, and 460 volts.

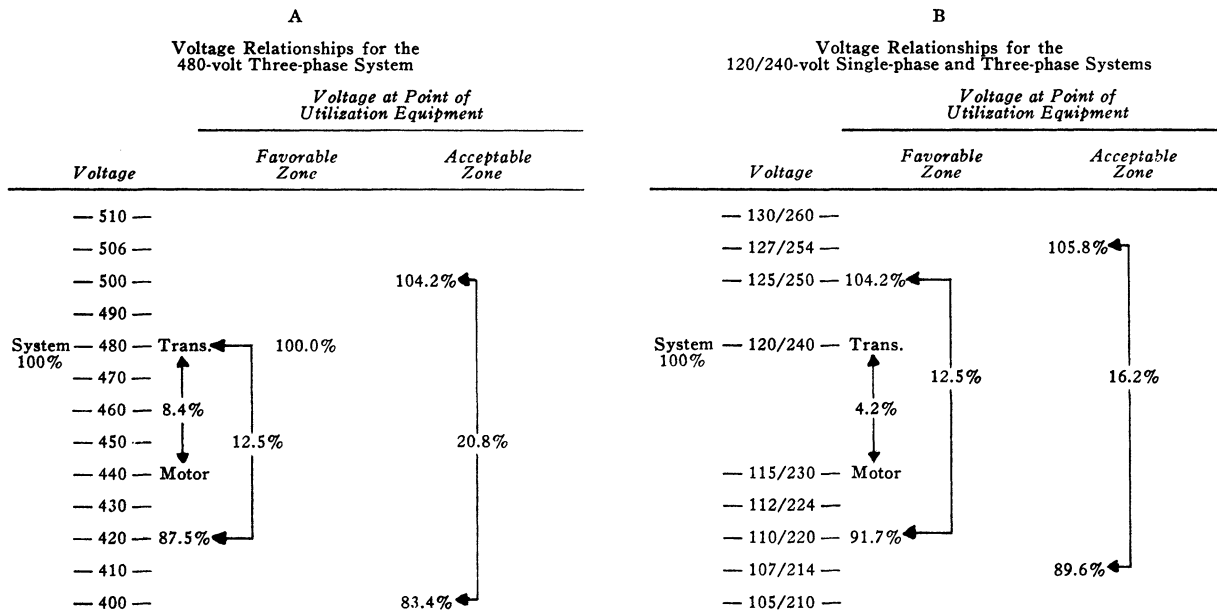
However, objections were raised to this proposal because of the problems of lowering existing supply voltages, the need for changing the distribution transformer Standards, and the incompatibility of this Standard with the 208-volt system. Yet the need to review the present Standard was quite apparent, so early in 1962 the American Standards Association (now the United States of America Standards Institute) Sectional Committee C84.1 was reactivated with representatives from all sectors of the electrical industry to revise the 1954 Standard.

Voltage Survey

The first major task of the new C84 Committee was to undertake a comprehensive voltage survey of the electric utility industry in the United States to determine the voltages in use, their relative importance, the trend in importance, the design policies for distribution systems and voltage control, and actual readings of voltages in the field. This report was completed and submitted to the committee in 1965. In general, the report showed that the average operating voltages for the various systems were very close to the nominal values in the existing Standard (120, 208, 240 and 480 volts for low-voltage systems) and the variations from nominal approximated the limits specified in the Standard. A portion of the results of the survey was published in the January 1966 issue of the *EEI Bulletin* (in an article, "65000 Service Voltage Tests Across the USA," by J. W. Anderson, Chairman of the Voltage Survey Subcommittee of USA Standards Committee C84).⁷

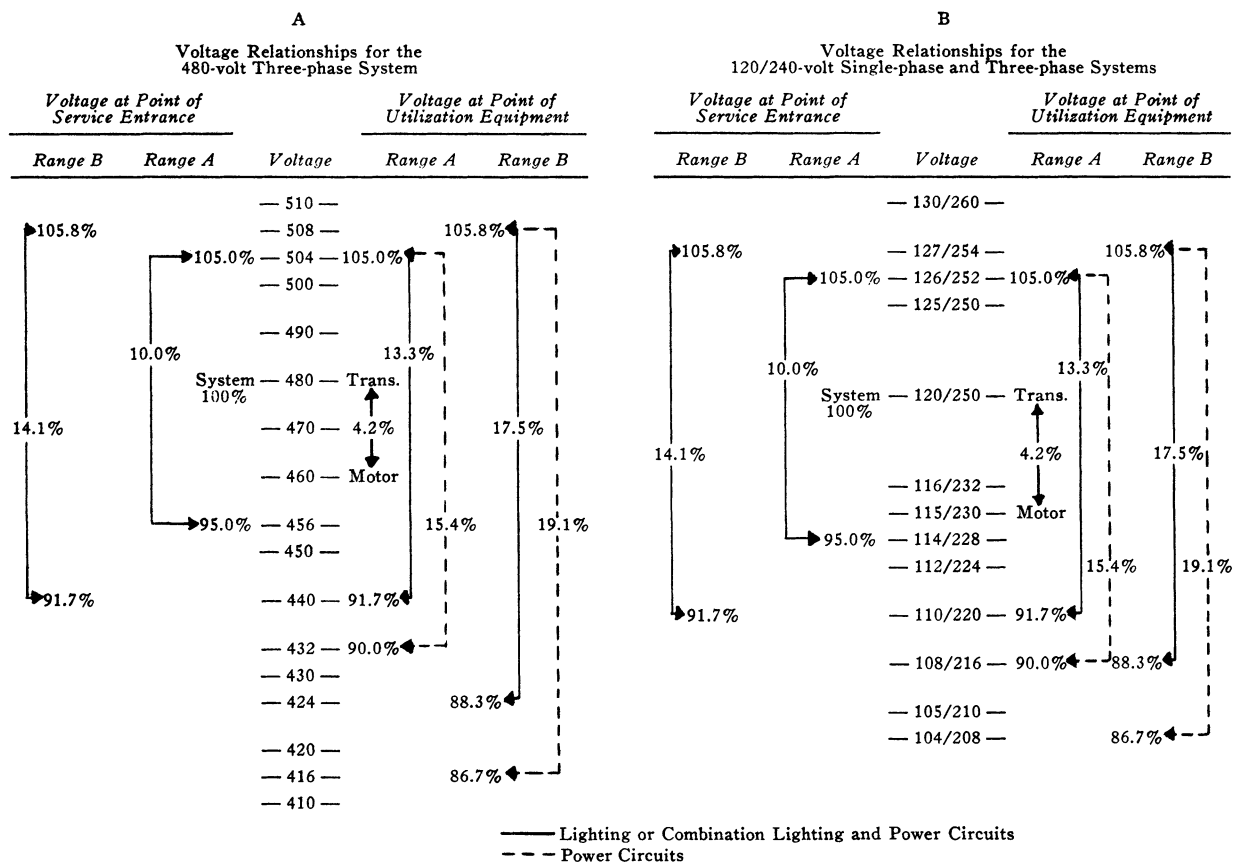
Voltage Relationships from 1954 ASA C84

CHART 1



Voltage Relationships from Proposed 1969 USAS C84

CHART 2



System to 240, 480, and 600 Volts— Motors to 230, 460, and 575 Volts

While this survey was being made, the motor manufacturers in NEMA reached the conclusion that a rerating program^{8,9} was possible because of improved materials, particularly at higher temperatures, and the improved art of design. In their design studies it was important that not only the voltage supplied to the motors be maintained within plus-or-minus ten percent of the utilization voltage, but also that the right voltage be established. Many users were pressing for higher design voltages and the C84 survey confirmed a definite need. A survey of voltages by NEMA motor manufacturers (indicating that the average voltage at the motor terminals of a 440-volt motor was 450 to 460 volts) added to the evidence. Also, many problems in the field indicated a great number of overvoltage problems. Thus the NEMA Motor and Generator Section established a Standard for future design in 1965, raising the voltage rating of motors to 230, 460, and 575 volts for 240-, 480-, and 600-volt systems.

A separate line of standard motors will be required for 208-volt systems; the increase in motor voltage operating range from 208-220 volts to 208-230 volts would handicap the 230×460-volt design. The preference is for 200 volts since this rating puts *all* low-voltage motors on a consistent 115-volt base.

This change places most low-voltage motors on a 115-volt base which is 4.2 percent below the system nominal voltage on a 120-volt base. Chart 1 shows the voltage relationships for the present 480-volt three-phase system and illustrates the disharmony with the 120/240-volt single-phase systems (or 240/120-volt three-phase system shown in Table 2.7) found in C84. Chart 2 shows the change to the proposed new Range A and Range B voltage based on the motor now being on a 115-volt base. (Chart 2 applies equally well to the 230- and 575-volt motors and their 240- and 600-volt systems, respectively.)

The plus-and-minus ten percent tolerance of the 115-volt motor permits the voltage applied to the motor terminals to vary from a maximum of 126.5 to a minimum of 103.5 volts. In terms of the system voltage this is a voltage variation from plus 5.42 percent to minus 13.75 percent, for a total swing of 19.17 percent. The problem now is to determine how much of this system voltage swing should be allotted to provide an adequate and workable allowance for variations in the supply voltage and how much should be allotted to provide for an adequate and workable allowance for the voltage drop in the wiring between the supply connection and the motor.

These charts show the extreme limits of the voltage swing. It is expected that the new Standard will provide for a limited voltage spread which will cover the majority of the voltages in service and limit the maximum spread to unusual conditions.

Influence on Power Distribution System Design

The problem of designing an electric power distribution system which will maintain the supply voltage to all customers within acceptable limits is illustrated in Figure 2.1, which shows the voltage profile of an electric distribution

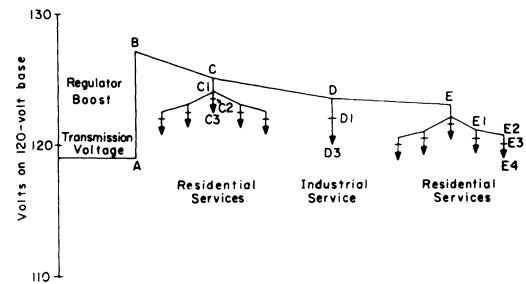


Figure 2.1
Voltage profile of a distribution system
120-volt base average conditions

system on a 120-volt base. (This figure is similar to Figure 2 of Appendix A, "Discussion of the Background for the Report," as a part of ASA C84.) A transmission line supplies a distribution substation with some voltage represented by point *A*. This is the voltage that would be supplied to a large industrial plant taking service directly from a subtransmission line at 69000 to 138000 volts. Transformers in the substation step the subtransmission voltage down to a distribution voltage; the most popular for an industrial plant is 4160 or 13800 volts. (Of course, the supplying electric utility may have other system voltages in this class based on its total system economics.) This is also represented by point *A* since the use of the 120-volt base cancels out the transformation. Automatic voltage regulators, either built into the transformer or installed separately, maintain the distribution voltage represented by point *B* regardless of changes in the transmission voltage. The regulators also raise and lower the distribution voltage slightly to compensate for the changes in the voltage drop along the feeder as the feeder load increases and decreases, as represented by the declining voltages at points *C*, *D*, and *E*.

Transformers are installed along the feeder to step the distribution voltage down to utilization voltages under 600 volts. The first transformer from the substation is shown at *C*. There will be a voltage drop through the transformer represented by *C*-*C1*. Under average conditions the maximum voltage will be received by the customer connected closest to the transformer *C* since his voltage will be reduced from the value at the transformer terminals by the voltage drop in the service represented by *C1*-*C2* and the voltage drop in the building wiring represented by *C2*-*C3*. In low load-density areas secondary wiring may be run from the transformer to adjacent poles to serve additional customers, in which case the voltage received by these customers will be further reduced by the voltage drop in the secondary as shown by the diagram.

The minimum voltage under average conditions will be received by the farthest customer from the last transformer on the feeder shown at *E*. The voltage he receives will be reduced below that received by the customer at *C3* by the voltage drop along the feeder represented by the declining values from *C* to *E* plus the voltage drop in the secondary represented by the declining values from *E1* to *E2*.

A service is shown at point *D* to an industrial plant having its own transformers. In this case there are no secondary and service voltage drops but the transformers are usually of larger rating with a higher impedance and hence a higher voltage drop than the usual distribution transformer; also, industrial plant wiring is usually much longer and more heavily loaded, so the wiring voltage drop is much higher than in a residence.

It should be pointed out that this diagram illustrates a continuously varying situation. Voltage drops change as loads are switched on and off. Cooking load comes on at mealtime. Lighting load comes on at night. Industrial and commercial load is generally turned off at night and on Sundays. Heating load comes on in the winter time and cooling load in the summer. New electric equipment is purchased. So, the voltage delivered to the terminals of a piece of electric equipment varies not only from minute to minute but also from hour to hour, day to day, and year to year.

The ends of utility feeders are usually equipped with switches to permit a feeder to be tied to an adjacent feeder in cases of emergency when the supply equipment has failed or the feeder conductor or supporting poles have been damaged. In such cases the length and load on a feeder is increased so the voltage drop is increased during the emergency. Under these conditions the voltage supplied to a motor may drop below the limits of the *favorable zone* but will still be within the minimum ten percent tolerance of the motor.

Engineering Approach to Voltage Zones

Based on the concepts given in Appendix A of ASA C84 (and illustrated by Figure 1), a proposed standard voltage profile for low-voltage systems can now be developed. This is shown in Table 2.7.

MEDIUM-VOLTAGE SYSTEMS

Medium-voltage systems are presently defined as those systems whose nominal values of voltage fall between 601 and 15000 volts.² Unlike low-voltage systems, medium-voltage systems are predominately used to supply secondary unit substations and distribution transformers, which in turn step the medium voltage down to a utilization voltage in the low-voltage range. Therefore, the voltage limits for medium-voltage systems must be established by determining the voltage limits which, when applied to the primary terminals of a supply transformer, will allow for the voltage drop in the transformer and secondary connections, and still provide a proper secondary service voltage.

The present USA Standard for system voltages³ is reproduced in Table 2.1. The 7200-volt three-phase system is obsolete and should be dropped from Table 2.1 and the 13800-volt system is now an accepted Standard. With these changes, Table 2.8 shows the voltage limits for medium-voltage systems.

The extrapolation of the base voltage values to produce the limits for medium-voltage systems in Table 2.8 requires that the ratios of the supply transformers used to make the transformation from the medium voltage to the low voltage as shown on the transformer nameplates be identical to the nominal values of the two voltages. The use of transformers with nameplate ratings other than

identical to the nominal system voltage values (which occurs in the case of: 1) transformers with primary nameplate ratings over 13800 volts, or 2) old transformers with secondary voltage ratings on other than a 120-volt base, or 3) the use of taps to change the transformer ratio for purposes other than to make the actual ratio agree with the nominal system voltage ratio) will change the voltage relationships given in Table 2.8.

Comparison with the Present Standard

The voltage limits for medium-voltage systems corresponding to the calculated limits for primary service voltages in Table 2.8 are given in the section of the present Standard in Table 2.1 headed *Primary Voltages at Distribution Transformers*. A comparison between the values given in these two tables shows that the voltage limits for the *tolerable zone* in the present Standard exceed both the maximum and minimum values given in Table 2.8, indicating that severe overvoltages and undervoltages could occur on the low-voltage utilization equipment if the medium voltages approached the maximum and minimum limits indicated. Even in the *favorable zone*, the minimum voltage limits are exceeded in the case of the 12000-volt and 14400-volt systems.

In Table 2.1 in IEEE Recommended Practice No. 92² the voltage limits for medium-voltage systems were based on the present Standard in Table II headed *Voltages at Point of Utilization by Equipment*. The information is given as Table 2.9. In this case a comparison between the values in these two tables shows that the voltage limits for the *tolerable zone* in the present Standard are the same for the maximum values but still lower for the minimum values. For the *favorable zone* the maximum and minimum values are both less than Table 2.8.

Medium-Voltage Utilization Equipment

The direct connection of utilization equipment to medium-voltage systems is recognized in the present Standard as shown in Table 2.1 by the extension of the section of the Standard headed *Voltages at Point of Utilization by Equipment* to include medium voltages up to 7200 volts. Table 2.10 shows the five standard medium voltages currently used in industrial plants for medium-voltage distribution, the nameplate rating of the standard motor for use on each system, and the plus and minus ten percent tolerance limits of the motors.

A comparison between *tolerable zone* limits for the *voltages at point of utilization by equipment* and the plus and minus ten percent limits for the motors shows very close agreement indicating that values listed in the present Standard are based on the voltage tolerances of the medium-voltage motors. However, a comparison of the tolerance limits for medium-voltage motors in Table 2.10 and the tolerance limits for Range B for primary service voltages from Table 2.8 shows that the maximum limits agree very closely but the minimum limits for *primary service voltages* are much higher due to the voltage drop allowance for the transformer and secondary system. However, the limits for *primary service voltages* in all cases are within the tolerance limits of the motors so that if the voltage is satisfactory to supply a transformer, it will be satisfactory for the motor.

Table 2.7

Proposed Standard System Voltages for Low-voltage Systems

Nominal System Voltage (Note a) Bold type—Preferred voltage Light type—In use but not preferred			Voltage Range A		Voltage Range B									
Single-phase Systems	Three-phase Systems		Minimum	Maximum	Minimum	Maximum								
		 Three-wire Wye or Delta	 Four-wire Wye or Delta	Utilization Voltage (Note c)	Service Voltage	Utilization and Service Voltage (Note e)								
Two-wire	Three-wire			Utilization Voltage (Note c)	Service Voltage	Utilization and Service Voltage								
LOW-VOLTAGE SYSTEMS														
120			110	91.7%	114	95.0%	126	105.0%	106	88.3%	110	91.7%	127c	105.8%
	120/240		110/220	91.7%	114/228	95.0%	126/252	105.0%	106/212	88.3%	110/226	91.7%	127/254c	105.8%
		208Y/120	191Y/110	91.7%	197Y/114	95.0%	218Y/126	105.0%	184Y/126 (Note d)	88.3%	191Y/110 (Note d)	91.7%	220Y/127c	105.8%
		240	220	91.7%	228	95.0%	252	105.0%	212	88.3%	220	91.7%	254c	105.8%
		240/120b	220/110	91.7%	228/114	95.0%	252/126	105.0%	212/106	88.3%	220/110	91.7%	254/127c	105.8%
		480	440	91.7%	456	95.0%	504	105.0%	424	88.3%	440	91.7%	508c	105.4%
		480Y/277	440Y/254	91.7%	456Y/263	95.0%	504Y/291	105.0%	424Y/245	88.3%	440Y/254	91.7%	508Y/293c	105.4%

EXPLANATION OF TERMS

Nominal Voltage
The nominal voltage of a circuit or system is a nominal value assigned to the circuit or system for the purpose of conveniently designating its voltage class.

Service Voltage
Service voltage is the voltage at the point where the electric systems of the supplier and the user are connected.

Utilization Voltage
Utilization voltage is the voltage at the line terminals of utilization equipment.

neutral conductor is also carried out from the source for connection of loads. Four-wire systems in Table 2.7 are designated by the phase-to-phase voltage, followed by the letter Y (except for the 240/120-volt delta system), a slant line, and the phase-to-neutral voltage. The principal transformer connections that are used to supply single-phase and three-phase systems are illustrated in Appendix A.

(b) The 600-volt system was omitted at this time in that the limits have not been resolved.

(c) Minimum utilization voltages for 120-600-volt circuits not supplying lighting loads are as follows:

(d) Many 220-volt motors were applied on existing 208-volt systems on the assumption that the utilization voltage would not be less than 187 volts. Caution should be exercised in applying the Range B minimum voltages of Table 2.7 and Note (c) to existing 208-volt systems supplying such motors.

(e) For 120-600 volt nominal systems, voltages in this column are maximum service voltages. Maximum utilization voltages would not be expected to exceed 125 volts for the nominal system voltage of 120, nor appropriate multiples thereof for other nominal system voltages through 600 volts.

(f) Low-voltage relationship of industrial transformers, and motor and control:

<i>Nominal System Voltage</i>	<i>Range A</i>	<i>Range B</i>
120	108	104
208	187	180 (Note d)
240	216	208
480	432	416
600	540	520

Three-phase Transformer	Three-phase Motor and Control	Single-phase Motor and Control
600Y/346V	575V	460V
480Y/277V	460V	230V
240Y/139V	230V	115V
208Y/120V	200V	

NOTES:

(a) Three-phase three-wire systems are systems in which only the three phase conductors are carried out from the source for connection of loads. The source may be derived from any type of three-phase transformer connection, grounded or ungrounded. Three-phase four-wire systems are systems in which a grounded

Table 2.8

Nominal System Voltage	Range A		Range B	
	Minimum 97.5 Percent	Maximum 105.0 Percent	Minimum 95.0 Percent	Maximum 105.83 Percent
2400*	2340	2520	2280	2540
4160*	4050	4370	3950	4400
4800*	4680	5040	4560	5080
6900	6730	7260	6550	7300
8320	8100	8740	7900	8800
12000	11700	12600	11400	12700
12470	12160	13090	11850	13200
13200	12870	13860	12540	13970
13800*	13460	14490	13110	14600
14400†	14041	15120	13680	15240

* Standard voltages used in industrial plants as well as utility systems.

† Requires 13800-volt transformer with taps set on 14400 volts.

Table 2.9

	Voltage	Percent of System Voltage	Voltage Spread, Percent
Favorable zone: maximum voltage	2450	102.1	+2.1
System nominal voltage and transformer voltage rating	2400	100.0	10.4
Motor voltage rating	2300	95.9	
Favorable zone: minimum voltage	2200	91.7	
Favorable zone: maximum voltage	4240	102.1	+2.1
System nominal voltage and transformer voltage rating	4160	100.0	10.4
Motor voltage rating	4000	96.1	
Favorable zone: minimum voltage	3810	91.7	
Favorable zone: maximum voltage	4900	102.1	+2.1
System nominal voltage and transformer voltage rating	4800	100.0	10.4
Motor voltage rating	4600	95.9	
Favorable zone: minimum voltage	4400	91.7	
Favorable zone: maximum voltage	7050	102.1	+2.1
System nominal voltage and transformer voltage rating	6900	100.0	10.4
Motor voltage rating	6600	95.7	
Favorable zone: minimum voltage	6320	91.7	
Favorable zone: maximum voltage	14100	102.1	+2.1
System nominal voltage and transformer voltage rating	13800	100.0	10.4
Motor voltage rating	13200	95.7	
Favorable zone: minimum voltage	12630	91.7	

Table 2.10

Nominal System Voltage	Rated Voltage of Motor	110 Percent of Motor Rating	90 Percent of Motor Rating
2400	2300	2530	2070
4160	4000	4400	3600
4800	4600	5060	4140
6900	6600	7260	5940
13800	13200	14520	11880

Table 2.11

Transformer Primary Nameplate Voltage	Nominal System Voltage	Range A		Range B	
		Mini- mum 97.5 Percent	Maxi- mum 105.0 Percent	Mini- mum 95.0 Percent	Maxi- mum 105.83 Percent
22900	20780Y/12000	20260	21820	19740	21990
	22860Y/13200	21290	24000	21720	24190
	23000	22330	24050	21860	24240
	23900Y/13800	23300	25100	22700	25290
34400	24900Y/14400	24280	26150	23650	26350
	34500 and 34500Y/19920	33540	36120	32680	36410
43800	46000	45050	48510	43890	48890
67000	69000	67080	72240	65360	72810

Since a medium-voltage distribution system supplying only medium-voltage motors would be unusual, the voltage limits for medium-voltage systems must be based on the requirements to supply transformers (and not on the requirements of medium-voltage motors). The only purpose for allowing a lower voltage at the utilization equipment would be to provide for an additional drop in the building wiring as done for the low-voltage system. However, voltage drop is rarely a factor in medium-voltage systems. For example, the 210-volt difference between the minimum voltage limit of the 2300-volt motor and the minimum voltage required to supply a 2400-volt transformer represents one and one-half miles of fully loaded cable while the 1230-volt difference between the minimum-voltage limit of the 13200-volt motor and the minimum voltage required to supply a 13800-volt transformer represents approximately eight miles of fully-loaded cable.

Feeders anywhere near this length would require special consideration and should not be the subject of a Standard. Since the voltage limits required to supply transformers as given in Table 2.8 will provide satisfactory service to the motors, there is no reason to consider voltage limits for utilization equipment on medium-voltage systems. If necessary, the actual voltage tolerance of equipment can be obtained by reference to the equipment Standards.

HIGH-VOLTAGE SYSTEMS

Until the National Electrical Code was changed in 1959, the maximum voltage which could be brought into a building for primary distribution was 15000 volts, except with special construction features. (This same limit also applied, for the most part, to the regulated voltages used by utilities to supply distribution transformers.) Thus, when the present Standard was being prepared, a clear distinction existed between medium voltages and the unregulated transmission and subtransmission voltages used by utilities to supply substations.

The increase in load densities in recent years and the movement of industrial plants and commercial buildings into the suburban and rural areas outside the cities have created problems in providing adequate distribution capacity at a reasonable cost. One solution has been to convert subtransmission lines in the range from 15000 to 35000 volts to distribution systems by connecting distribution transformers to them. Another solution has been to convert three-wire systems in the upper medium-voltage range to 4-wire by changing the phase-to-phase voltage to a phase-to-neutral voltage in the same way that the 2400-volt system has been largely converted by utilities to 4160Y/2400 volts. As a result, the demarcation between distribution voltages under 15000 volts and subtransmission voltages over 15000 volts has largely disappeared. The present Standard for distribution transformers¹⁰ provides for primary voltages up to 69000 volts.

This development requires that Table 2.8 listing the voltage limits for primary services should be extended up to 34500 volts (and up to 69000 volts if correlation with the distribution transformer Standard is desired). This extension is given in Table 2.11 which is based on the percentage values for primary service voltages as were used in Table 2.8. (This is also shown in Table 2.12.)

VOLTAGE RATINGS FOR 60-HERTZ ELECTRIC POWER SYSTEMS

Explanation of Terms

Nominal Voltage

The nominal voltage of a circuit or system is a nominal value assigned to the circuit or system for the purpose of conveniently designating its voltage class.

Service Voltage

Service voltage is the voltage at the point where the electric systems of the supplier and the user are connected.

Utilization Voltage

Utilization voltage is the voltage at the line terminals of utilization equipment.

Selection of Nominal System Voltages

When a new system is to be built or a new voltage level introduced in an existing system, it is recommended that one (or more) of the nominal system voltages shown in bold face type in Table 2.1 be selected. The logical and economical choice for a particular system among the voltages thus distinguished will depend upon a number of factors, such as the character and the size of the system.

Other system voltages that are in substantial use in existing systems are shown in light face type. Economic considerations will require that these voltages continue in use and in some cases may require extension of their use; but they are not generally recommended for new systems or new voltage levels in existing systems.

The 4160-, 6900-, and 13800-volt three-wire systems are particularly suited for industrial systems that supply predominantly polyphase loads including large motors, because these system voltages correspond to the standard motor ratings of 4000, 6600, and 13200 volts. Two of these systems are shown in bold face type to indicate that their use for this purpose is recommended. It is not intended to recommend the use of these systems for utility primary distribution, for which four-wire systems of 12470Y/7200 volts or higher are recommended.

Explanation of Voltage Ranges

For any specific nominal voltage, the voltages actually existing at various points at various times on any power system, or on any group of systems, or in the industry as a whole, will be distributed by percentage in some such manner as indicated by Figure 2.2. This distribution is characteristic of voltages at any designated class of points, such as points of service delivery and points of utilization. It is important that the design and operation of power systems and the design of equipment to be supplied from such systems be coordinated with respect to these voltage variations so that, insofar as practicable, the equipment will perform satisfactorily throughout the range of actual utilization voltages that will be encountered on the systems. In order to further this objective, this Standard establishes for each nominal system voltage, two ranges for service and utilization voltage variations, designated as Range A and Range B, the limits of which are given in Table 2.1. These limits apply to sustained voltage levels and not to momentary voltage excursions that may result from such causes as switching operations, motor starting currents, etc.

Application of Voltage Ranges

Range A: Service Voltage

Electric supply systems shall be so designed and operated that most service voltages are within the limits specified for this range. The occurrence of service voltages outside of these limits is to be infrequent with respect to time and place.

Range A: Utilization Voltage

User systems shall be so designed and operated that, with service voltages within Range A limits, most utilization voltages are within the limits specified for this range.

Utilization equipment shall be designed and rated to give fully satisfactory performance throughout this range.

Range B: Service and Utilization Voltages

This range includes voltages above and below Range A limits that necessarily result from practical operating conditions on supply and/or user systems. Although such conditions are a part of practical operations, they shall be limited in extent, frequency and duration. When they occur, corrective measures shall be undertaken within a reasonable period of time to improve voltage to within Range A limits.

Insofar as practicable, utilization equipment shall be designed to give acceptable performance in the extremes of this range of utilization voltage, although not necessarily as good performance as in Range A.

It must be recognized that, because of conditions beyond the control of the supplier and/or user, there will be infrequent and limited periods when sustained voltages outside of Range B limits will occur. Utilization equipment may not operate satisfactorily under these conditions, and protective devices may operate to protect the equipment. When voltages occur outside the limits of Range B, prompt corrective action is recommended. The urgency for such action will depend upon many factors, such as location and nature of load or circuits involved, and magnitude and duration of the deviation beyond Range B limits.

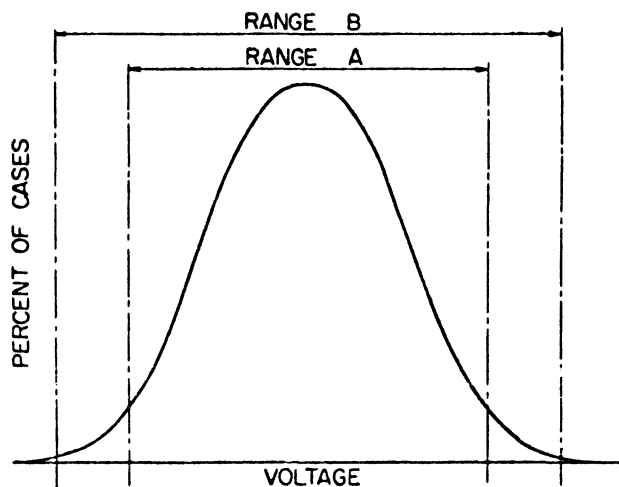


Figure 2.2
Distribution Characteristics of System Voltages

Table 2.12
Standard System Voltages

NOMINAL SYSTEM VOLTAGE (Note a)			VOLTAGE RANGE A (Note b)			VOLTAGE RANGE B (Note b)		
			Minimum		Maximum	Minimum		Maximum
Two-wire	Three-wire	Four-wire	Utilization Voltage (Note c)	Service Voltage	Utilization and Service Voltage (Note e)	Utilization Voltage (Note c)	Service Voltage	Utilization and Service Voltage
Single-phase Systems								
120	120/240		110 110/220	114 114/228	126 126/252	106 106/212	110 110/220	127 127/254
Three-phase Systems								
		208Y/120	191Y/110	197Y/114	218Y/126	184Y/106 (Note d)	191Y/110 (Note d)	220Y/127
	240	240/120	220/110	228/114	252/126	212/106	220/110	254/127
	480	480Y/277	440Y/254	456Y/263	504Y/291	424Y/245	440Y/254	508Y/293
	2400		440 2160	456 2340	504 2520	424 2080	440 2280	508 2540
	4160	4160Y/2400	3740Y/2160	4050Y/2340	4370Y/2520	3600Y/2080	3950Y/2280	4400Y/2540
	4800		3740 4320	4050 4680	4370 5040	3600 4160	3950 4560	4400 5080
	6900		6210	6730	7240	5940	6560	7260
		8320Y/4800	X	8110Y/4680	8730Y/5040	X	7900Y/4560	8800Y/5080
		12000Y/6930		11700Y/6760	12600Y/7270		11400Y/6580	12700Y/7330
		12470Y/7200		12160Y/7020	13090Y/7560		11850Y/6840	13200Y/7620
		13200Y/7620	(Note f)	12870Y/7430	13860Y/8000	(Note f)	12540Y/7240	13970Y/8070
		13800Y/7970		13460Y/7770	14490Y/8370		13110Y/7570	14520Y/8380
	13800		12420	13460	14490	11880	13110	14520
		20780Y/12000	X	20260Y/11700	21820Y/12600	X	19740Y/11400	22000Y/12700
		22860Y/13200		22290Y/12870	24000Y/13860		21720Y/12540	24200Y/13970
				22430	24150		21850	24340
	23000	24940Y/14400	(Note f)	24320Y/14040	26190Y/15120	(Note f)	23690Y/13680	26400Y/15240
		34500Y/19920		33640Y/19420	36230Y/20920		32780Y/18930	36510Y/21080
	34500			33640	36230		32780	36510

Higher Voltage
Three-phase Systems in kV

Nominal System Voltage	Maximum Voltage
46	48.3
69	72.5
115	121
138	145
161	169
230	242

For these systems Range A and Range B limits are not shown because, where they are used as service voltages, the operating voltage level on the user's system is normally adjusted by means of voltage regulation to suit his requirements.

Extra High Voltage
Three-phase Systems in kV

Preferred Nominal System Voltage	Preferred Maximum Voltage
345	362
500	550
700	765

Information from USA Standard C92.2—1967.

NOTES:

(a) Three-phase three-wire systems are systems in which only the three phase conductors are carried out from the source for connection of loads. The source may be derived from any type of three-phase transformer connection, grounded or ungrounded. Three-phase four-wire systems are systems in which a grounded neutral conductor is also carried out from the source for connection of loads. Four-wire systems in Table 2.12 are designated by the phase-to-phase voltage, followed by the letter Y (except for the 240/120-volt delta system), a slant line, and the phase-to-neutral voltage. The principal transformer connections that are used to supply single-phase and three-phase systems are illustrated in Appendix A.

(b) The 600-volt system was omitted at this time in that the limits have not been resolved.

(c) Minimum utilization voltages for 120-600 volt circuits not supplying lighting loads are as follows:

Nominal System Voltage	Range A	Range B
120	108	104
208	187	180 (Note d)
240	216	208
480	432	416
600	540	520

(d) Many 220-volt motors were applied on existing 208-volt systems on the assumption that the utilization voltage would not be less than 187 volts. Caution should be exercised in applying the Range B minimum voltages of Table 2.12 and Note (c) to existing 208-volt systems supplying such motors.

(e) For 120-600 volt nominal systems, voltages in this column are maximum service voltages. Maximum utilization voltages would not be expected to exceed 125 volts for the nominal system voltage of 120, nor appropriate multiples thereof for other nominal system voltages through 600 volts.

(f) Utilization equipment does not generally operate directly at these voltages. For equipment supplied through transformers refer to limits for nominal system voltage of transformer output.

In preparing Table 2.11, a column was added to list the primary nameplate voltage of the transformer because above 13800 volts, the transformer primary nameplate voltage and the system nominal voltage are not identical. The voltage limits should be based on the actual transformer ratio and not the system nominal voltage. This is an area that needs additional study to determine the values of having the system nominal voltage and transformer voltage the same, as with the present low-voltage and medium-voltage systems.

Voltages at Substations and on Transmission Systems

The present Standard provides voltage limits for medium voltages at *substations and on transmission systems* and this now falls in the medium-voltage system classification. The values given for minimum voltages are the same as those given for *primary voltages at distribution transformers*, but the maximum values are higher.

These figures do not seem to serve any useful purpose. The values are far beyond the limits provided in Table 2.8 to serve distribution and other supply transformers. The only other purpose would be to establish maximum and minimum limits for voltages applied to substation and transmission line equipment, but these requirements could be covered much better by a reference to the appropriate equipment Standard.

Need for Improved System Voltage Nomenclature

The approach developed for low-voltage¹¹ systems and extended to medium-voltage¹² systems results in the development of a table of Standard System Voltages, Table 2.12. This table represents major progress from the approach found in Table 2.1 representing the present Standard, and provides a sound, workable basis for integrating the customers' requirements with the utility supply system.¹³

TRANSFORMER VOLTAGE REPRESENTATIONS

Transformer voltage designations become rather complex. For instance, windings may have series-parallel connections; or they may be designed for connection line-to-neutral on higher rated voltage systems, such as 2400-volt transformers which are suitable for line-to-neutral operation on 4160-volt systems. These and other complex arrangements make exact identification desirable.

These variables in transformer voltage ratings have long been expressed by various symbolic methods. Such methods are essential because to describe fully the windings of transformers often would require a fairly lengthy paragraph. However, to be of any value, a transformer rating so expressed should mean the same to everyone. To further a consistent use of symbols, both NEMA and USA Standards have been established to recommend a standard transformer "shorthand."

Four symbols are used: the dash (—), the slant (/),

the X and the Y. In general terms, their uses are as follows:

Dash (—) Used to separate the voltage ratings of separate windings in a specific transformer.

Slant (/) Used to separate voltages to be applied to or obtained from the same winding. The slant may be used to designate voltages derived by taps or by line-to-neutral connections.

X—Used to designate separate voltages obtainable by reconnection of the coils of a winding in series or multiple combinations, but not for three-wire operation.

Y—Used to designate a winding that is wye-connected. The absence of this symbol in a three-phase transformer rating indicates that the winding is delta-connected.

SELECTION OF PROPER PLANT VOLTAGE LEVELS

The selection of system voltages in an industrial plant is, broadly speaking, an economic problem. However, a determination based on strict economic analysis may, in practice, be modified by plant or industry standardization, availability of equipment and construction materials and other factors. The economic analysis will take into consideration:

- (a) Class of service available from supplier.
- (b) Total size of the installation.
- (c) Planning for future growth.
- (d) Characteristics of the equipment supplied.
- (e) Density of the load.
- (f) Safety considerations and qualifications of personnel available for operation and maintenance.
- (g) Whether the installation is an extension or reconstruction of an existing plant, or whether it is a completely new, isolated installation.

For an extension to an existing plant, the principal decision to be made will be whether existing voltages can be used satisfactorily in the enlarged plant or whether in the interest of long-range economy, a different (usually higher) voltage should be boldly selected for the new equipment. In the latter case, there will be the temporary disadvantage of operating two different systems, either superimposed in the same building or separated in different buildings, the latter being the least objectionable. The superseded system may, in the future, become a small part of the total and ultimately disappear as processes change, as machines are moved about, and as motors are rewound.

There are several factors having a tremendous influence on the over-all cost and selection of system voltage; these are: the feeder circuits, switchgear, system fault duty, circuit arrangements, total motor horsepower, and motor horsepower ratings. It is beyond the scope of this chapter to cover these. However, refer to Chapters I and X. Since, in various voltage classes, different factors

have the most pronounced effect on voltage selection, the discussion of selection of voltage is divided into:

- (1) Selection of voltages 600 volts or less (low voltage)
- (2) Selection of voltages 601 to 34,500 volts (medium voltage)
- (3) Selection of voltages above 34,500 volts (high voltage)

Selection of Voltages 600 Volts or Less

In most industrial plants, the majority of loads are integral horsepower polyphase motors and welders which are most suitable for operation on systems 600 volts or less. The choice of nominal system voltages in this class for serving these loads is 208, 240, 480 (or 480Y/277), or 600 volts. These are compared in Figure 2.3.

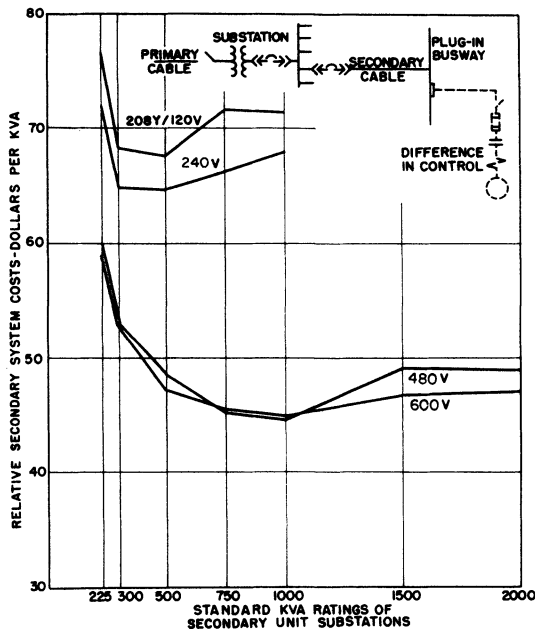


Figure 2.3
Curve showing the approximate installed costs of 208-, 240-, 480- and 600-volt radial secondary systems

A brief comparison of these low-voltage systems follows:

480 versus 600-Volt Systems

Although 600-volt load-center systems cost about two to seven percent less (See Figure 2.3) than 480-volt load-center systems, they have decreased in popularity primarily due to the lack of availability of standard 550 and 575-volt utilization equipment from manufacturers' and distributors' stocks in the United States. This was brought out forcibly during World War II when the percentage of standard 550-volt induction motors decreased from 11 to 4 percent of the total standard induction motors made.

When ordering machine tools or other utilization equipment with considerable electric control circuits, it is often difficult to obtain 575 (or 550)-volt equipment, particularly

on short shipment. Pumps and other equipment which are stocked by the manufacturers with motors already mounted are generally stocked 230 (or 220) or 460 (or 440)-volt ratings and not with 575 (or 550)-volt ratings.

Availability of utilization equipment is the only major problem when choosing between 600-volt and 480-volt systems. Today, 600-volt systems are limited primarily to expansion of those plants which already operate at 600 volts or to some textile plants where most motors are of special design and, thus, are not widely available from manufacturers' stocks.

Another advantage of the 480-volt over the 600-volt system is the possibility of using 480Y/277-volt distribution with 277-volt fluorescent lighting.

480 versus 240-Volt Systems

Economically speaking, there is seldom any reason for selecting 240 volts instead of 480 volts. Load-center systems at 240 volts cost from 25 to 50 percent more (See Figure 2.3) than 480-volt load-center systems. Lower-voltage systems cost more because there is more current per kVA to be carried, thereby increasing the size of the circuit breakers and conductors required.

Generally 240-volt systems have higher losses and higher percentage voltage drop than 480-volt systems. If enough copper is used in the 240-volt feeders, the losses and percentage voltage drop can be more comparable to those in 480-volt systems, but in practice this is seldom done.

Some industries, where there is considerable dampness such as in dairies and slaughterhouses, have often selected 240 volts because it is felt to be safer than 480 volts. Operating records show that the biggest factor in safety is to properly and securely ground all non-current-carrying parts so that insulation breakdowns cannot place dangerous potentials on the non-current-carrying parts. When working on circuit conductors while energized, there is a greater chance for injury from electric shock with higher potentials to ground or phase-to-phase. However, any voltage above 50 volts can be lethal and, therefore, the only safe way to handle these circuits in damp or other locations is to enclose the carrying conductors in securely and properly grounded metal enclosures and to work on current-carrying parts only when they are deenergized.

In areas with the load predominantly electric furnaces, 240 volts may be most advantageous. This is due to the limitation of voltage which may be applied to these furnaces. In general, furnaces are large spot loads and cover only a small portion of the area of the plant. These furnaces, therefore, may be supplied by a separate load-center substation stepping down to 240 volts for the furnace only and the rest of the load supplied at 480 volts. It is seldom economical to use 240 volts for general distribution in a plant even though a sizeable portion of the total kW load may be 240-volt furnaces.

Where 208Y/120-Volt Systems Are Applicable

There are certain areas where 208Y/120-volt systems are more economical than 480-volt systems because the

types of utilization equipment involved must be operated at 120 volts. When such utilization equipment constitutes a major portion of the load (more than about 50 to 65 percent of the total load), 208Y/120-volt systems may be more economical than 480-volt systems.

Typical of such loads is that of a clothing manufacturing establishment where practically all of the power is utilized by motor-operated hand shears. Other areas in which 208Y/120 volts may be desirable are on assembly benches where small components are assembled and small portable tools such as soldering irons, electric hand drills, electric nut tighteners, etc., are used. A typical case would be a small electronic equipment assembly line. Again, the choice of the lower voltage is primarily based on the desire to limit the voltage in the hand tools to 120 volts. In these assembly areas, most of the power is utilized at this low voltage.

General Practice—Systems of 600 Volts and Less

As general practice, 480 volts is most widely used and recommended by engineers as a general secondary distribution voltage in industrial plants. Where a lower secondary system voltage is required 208Y/120 volts may be used, since it provides 120 volts for incandescent lamps, hand tools, etc. These two voltages should cover practically all requirements for secondary voltages for the modern industrial plant except for electric furnaces.

In factories where at least one-third to one-half the load can operate on 480-volt systems and the remainder of the load must operate at a lower voltage or where distances are greater than about 200 feet, 480-volt main distribution and small step-down transformer to 120 or 240 volts may be most economical.

One additional point which should be mentioned in connection with low-voltage distribution is the trend toward the 480Y/277-volt system. Such a system with the neutral readily available takes advantage of the savings inherent in the 480-volt system and, in addition, provides an economical method for supplying the lighting load. By extending the neutral circuit in the lighting feeders only, 277-volt fluorescent lighting can be distributed between the three phase conductors and neutral. The power load would be supplied at 480 volts from three-conductor, three-wire circuits. It is not necessary to extend the neutral circuit in the feeders supplying only power load.

Selection of Voltages for Systems of 601 Volts to 15 Kilovolts

Voltages in this class are used mainly for primary power distribution in industrial plants. All plants using a primary voltage employ voltages of this class except some of the very large chemical plants, steel mills, etc. The latter may employ subtransmission voltages above 15,000 volts.

When the utility voltage is below 15,000 volts, there is no problem of selecting the primary voltage.

Since the National Electrical Code permits 15,000 volts inside buildings, without special restrictions, there is gen-

erally no reason for transforming voltages of the order of 13,800 volts to, say, 2400 volts or 4160 volts for distribution through the building. The higher voltage can be carried to the load-center substations and there transformed to utilization voltage.

Above 15,000 volts, the National Electrical Code, Section 230-101 (h), states that service entrance conductors brought into a building must directly enter metal-enclosed switchgear or a transformer vault. Therefore, when the utility supply voltage is above 15,000 volts, transformation to some lower voltage is desirable both economically and technically for distributing the power through the plant to the load-center substations where it is stepped down to utilization voltage. (An exception to this is large steel mills, chemical plants, etc., having large widely-scattered loads.) The trend in the past few years has been toward selection of higher voltages to obtain greater economy and flexibility for expansion. Many studies have shown that either of two voltages will suffice in the majority of cases.

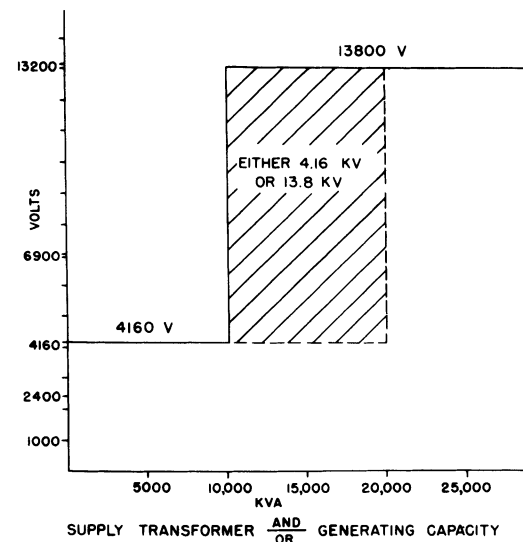


Figure 2.4
Chart showing most economical voltage for industrial plants

Figure 2.4; i.e., 4160 volts for plants having a supply transformer and/or generating capacity of 10,000 kVA and less, and 13,800 volts for plants having a supply transformer and/or generating capacity of 20,000 kVA or greater. For the range between 10,000 and 20,000 kVA either 4160 or 13,800 volts may prove to be more economical. While 4160 volts might be slightly less expensive for a 15,000 kVA plant, if the plant should happen to grow, then 13,800 volts would be more economical.

Where 2400 Volts is Particularly Applicable

In plants which are served at 2400 volts directly from the utility system, then, of course, it would be more economical to use 2400 volts directly and to place all motors rated 200 horsepower and above directly on the primary feeders. However, in these cases, most motors rated less than 200 horsepower should be operated on a 480-volt

system, stepping down from the 2400-volt primary system. In some cases, there are existing 2400-volt systems in industrial plants, and it is often more economical to extend these at 2400 volts rather than changing to 4160 volts. However, it may be more desirable to extend it at some higher voltage like 13,800 volts rather than to extend the system at 2400 volts.

Where the primary voltage is above 5000 volts, 2400 volts is applicable to concentrated loads which supply motors rated 200 horsepower and above. In these cases, it is preferable to step down from the higher voltage to 2400 volts rather than to 4160 volts, if the capacity per 2400-volt bus is limited to less than about 7500 kVA and nearly all of this load is utilized at this bus directly by motors rated above 200 horsepower. For single loads larger than 7500 kVA per bus with motors above about 250 horsepower, it is often necessary to go to 4160 volts to enable the switchgear to handle the short-circuit currents available from such large buses. A typical application where 2400 volts would be most economical is a pumping station, in which the control may be of the fused combination type to give fast short-circuit protection or of the circuit-breaker type where the frequency of starting is not too great. If this preference is followed, it will be necessary to make a transformation for these large motors. The cost of the transformation is substantially the same whether it is made to 2400 volts or to 4160 volts. Thus, the power system cost is not a significant factor as all of the load is concentrated in one place. The 2300-volt motors and their starters are less expensive than 4000-volt motors and their starters in most cases.

The influence of motors on choice between 2400 and 4160 volts as the primary system voltage is shown in Figure 2.5.

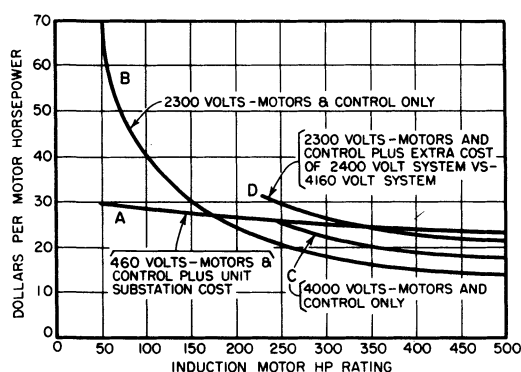


Figure 2.5
Approximate cost of induction motors and control and appropriate system costs as a function of motor horsepower

SYSTEM VOLTAGE VARIATION

An ideal electric power system is one which will supply constant frequency and voltage at rated nameplate value

to every piece of apparatus in the system. In modern power systems, frequency is a minor problem. It is impractical to design a power system which will deliver absolutely constant rated nameplate voltage to every piece of apparatus. Since this cannot be attained, what are the proper limits of voltage variations in an industrial plant? This should be determined by the characteristics of the utilization apparatus.

Definitions

Voltage drop in a distribution system is the difference at any instant between the voltages at the source and utilization ends of a feeder, branch circuit, or transformer.

Voltage spread is the difference between the maximum and minimum voltages existing in any one voltage-class system under specified steady-state conditions.

Voltage regulation is a measure of the change in voltage between no load and full load in terms of the full-load voltage.

Percent Regulation =

$$\frac{(\text{no-load volts}) - (\text{full-load volts})}{\text{full-load volts}} \times 100$$

Causes of Voltage Regulation

Voltage drop is caused by current flowing through an impedance such as a transformer, cable, reactor, or bus. The voltage regulation at the terminals of the utilization apparatus is caused by the regulation of the incoming supply voltage and the voltage drop in the power system within the industrial plant.

Let us examine a typical industrial plant. Figure 2.6 shows a simplified one-line diagram. Figure 2.7 shows the voltage profile for a particular set of conditions. Note that the no-load voltage is 490 volts. There is a 10-volt drop due to the spread in the primary system, in addition to the voltage drops in the various portions of the system. Note that the total spread is 30 volts, 20 of which is due to the regulation within the plant, so the normal operating voltage will be around 460 volts.

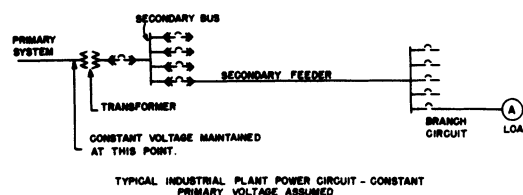


Figure 2.6
Simplified power system for studying voltage regulation



Figure 2.6a
A line-up of automatic induction voltage regulators
to maintain precise voltage on critical plating lines



Figure 2.6b
A closeup view of one regulator of the type shown in
Figure 2.6a

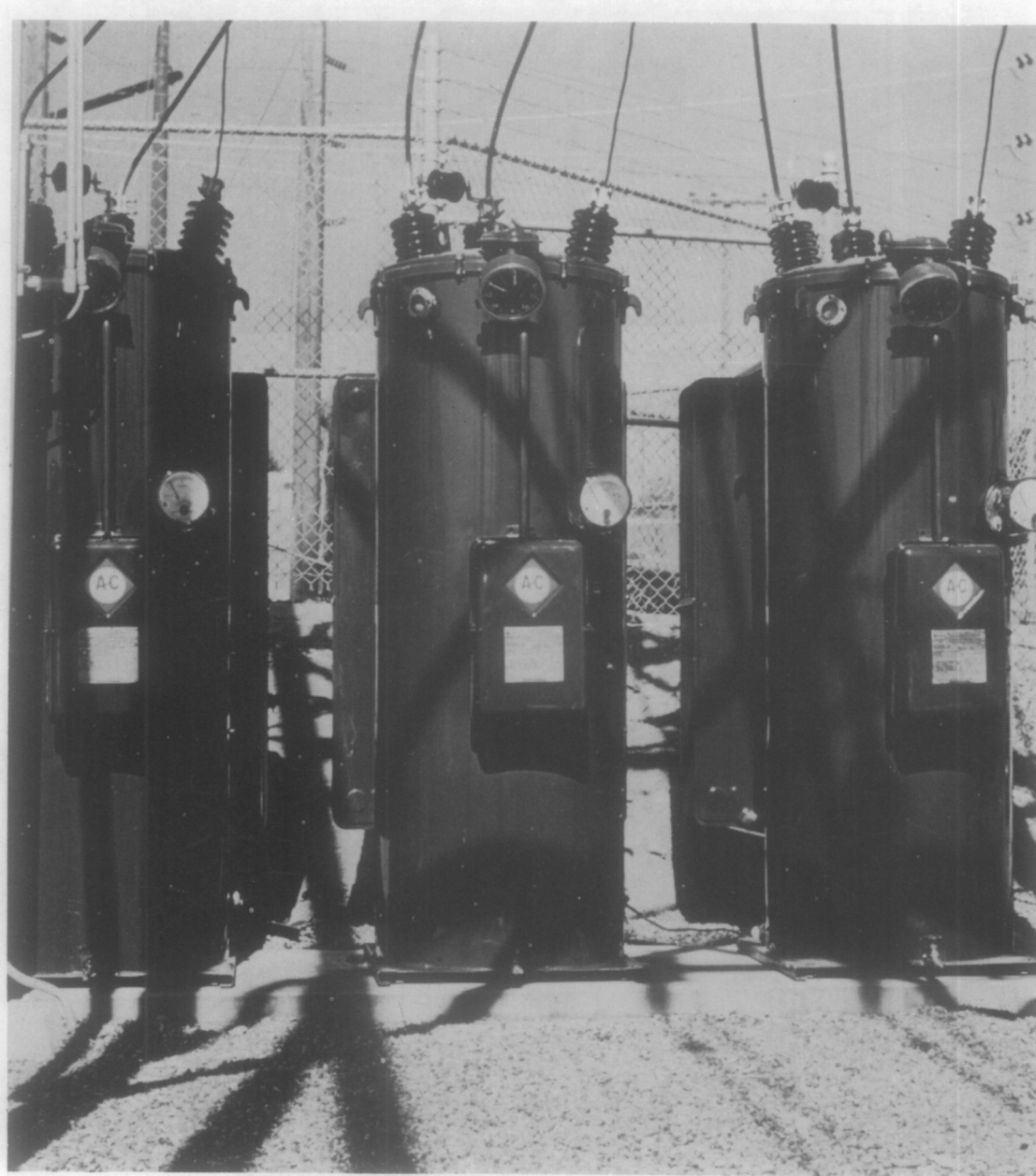


Figure 2.6c
Bank of outdoor voltage regulators for primary regulation