

IEEE Guide for the Design of Low-Voltage Auxiliary Systems for Electric Power Substations

IEEE Power and Energy Society

Sponsored by the
Substations Committee

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IEEE Guide for the Design of Low-Voltage Auxiliary Systems for Electric Power Substations

Sponsor

Substations Committee
of the
IEEE Power and Energy Society

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Abstract: Considered in this guide are the components of both the ac and dc systems and the provided guidelines and recommendations for designing the appropriate systems for the substation under consideration. This guide includes the low-voltage auxiliary systems from the source(s) to the distribution point(s). Reliability requirements and load characteristics are discussed and distribution methods are recommended.

Keywords: ac system, auxiliary systems, battery, dc system, IEEE 1818, low voltage, station power, station service

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Introduction

This introduction is not part of IEEE Std 1818-2017, IEEE Guide for the Design of Low-Voltage Auxiliary Systems for Electric Power Substations.

IEEE Guide 1818 was created by members of Working Group D9 and is under the sponsorship of the Substations Committee of the IEEE Power & Energy Society. This guide provides guidance and information to substation engineers on factors to consider in the design of ac and dc auxiliary systems for application in electric substations. This guide references several existing standards and is not intended to replace existing documentation, but to provide guidance for the application of ac and dc systems specifically in substation applications.

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IEEE Guide for the Design of Low-Voltage Auxiliary Systems for Electric Power Substations

1. Overview

1.1 Scope

This guide will consider the components of both the ac and dc systems and provide guidelines and recommendations for designing the appropriate systems for the substation under consideration. This guide covers the low-voltage auxiliary systems from the source(s) to the distribution point(s). Reliability requirements and load characteristics are discussed, and distribution methods are recommended.

1.2 Purpose

The low-voltage ac and dc auxiliary systems comprise very important parts of the substation equipment. The design of the ac and dc auxiliary systems facilitates the safe and reliable operation of the substation. This guide considers various factors that affect the design of the ac and dc auxiliary systems such as reliability, load requirements, system configurations, personnel safety, and protection of auxiliary systems equipment.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 485™, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications.^{1,2}

IEEE Std 525™, IEEE Guide for the Design and Installation of Cable Systems in Substations.

3. Definitions

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³*IEEE Standards Dictionary Online* subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

authority having jurisdiction (AHJ): The organization, office, or individual that has the responsibility and authority for approving equipment, installations, or procedures.

available short-circuit current: (at a given point in a circuit) The maximum current that the power system can deliver through a given circuit to any negligible-impedance short circuit applied at the given point, or at any other point that will cause the highest current to flow through the given point.

basic impulse insulation level (BIL): A reference impulse insulation strength expressed in terms of the crest value of the withstand voltage of a standard full impulse voltage wave.

battery duty cycle: The sequence of loads a battery is expected to supply for specified time periods.

cell size: The rated capacity of a cell, or the number of positive plates in a cell.

equalizing charge: A charge, at a level higher than the normal float voltage, applied for a limited period of time, to correct inequalities of voltage, specific gravity, or state of charge that may have developed between the cells during service.

extra-high voltage (EHV): A maximum system voltage that is greater than 242 kV but less than 1000 kV.

ferroresonance: (A) A phenomenon usually characterized by overvoltages and very irregular wave shapes and associated with the excitation of one or more saturable inductors through capacitance in series with the inductor. (B) An electrical resonant condition associated with the saturation of a ferromagnetic device, such as a transformer, through capacitance. Ferroresonance can arise when (1) due to dissimilar phase switching, the capacitance normally in shunt with the ferromagnetic device becomes energized in series with the device, (2) a weak source is isolated with a lightly loaded feeder containing power-factor-correction capacitors. For example, if the resulting voltage buildup produces saturation of the feeder transformers, there will be an interchange of energy between the system capacitance and the nonlinear magnetizing reactance of the transformers.

float charge: A constant-voltage applied to a battery to maintain it in a fully charged condition, while minimizing degradation or water consumption.

float service: Operation of a dc system in which the battery spends the majority of the time on float charge with infrequent discharge. *Syn:* standby service.

fully rated system: Every protective device is rated to at least the available fault current at the service point.

high voltage: A class of nominal system voltages equal to or greater than 100 000 V and equal to or less than 242 000 V.

low voltage: Voltage levels that are less than or equal to 1 kV.

medium voltage: A class of nominal system voltages greater than 1000 V and less than 100 000 V.

molded-case circuit breaker (MCCB): A circuit breaker that is assembled as an integral unit in a supporting and enclosing housing of insulating material.

nominal battery voltage: The value assigned to a battery of a given voltage class for the purpose of convenient designation. The operating voltage of the system may vary above or below this value.

nominal system voltage: The ac system voltage by which the system is designated and to which certain operating characteristics of the system are related.

pad-mounted transformer: An outdoor transformer utilized as part of an underground distribution system, with enclosed compartment(s) for primary-voltage and secondary-voltage cables entering from below, and mounted on a foundation pad.

panelboard: A single panel or group of panel units designed for assembly in the form of a single panel, including buses and automatic overcurrent devices, and equipped with or without switches for the control of light, heat, or power circuits; designed to be placed in a cabinet or cutout box placed in or against a wall, partition, or other support; and accessible only from the front. (Adapted from the NEC.) *See also:* **switchboard**.

period: An interval of time in the battery duty cycle during which the current (or power) is assumed to be constant for purposes of cell-sizing calculations.

rated capacity (lead-acid): The capacity assigned to a cell by its manufacturer for a given discharge rate, at a specified electrolyte temperature and specific gravity, to a given end-of-discharge voltage.

remote terminal unit (RTU): A piece of equipment located at a distance from a master station to facilitate monitoring and control the state of outlying power equipment and to communicate the information back to the master station or host.

separately derived system: A wiring system whose power is derived from a generator, transformer, or converter windings and has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system.

series rated system: Each protective device needs to only be rated for the available fault current at its terminals.

station service voltage transformer (SSVT): A transformer that supplies power from a station high-voltage bus to the station auxiliaries and also to the unit auxiliaries during unit startup and shutdown, or when the unit auxiliaries transformer is not available, or both.

switchboard: (A) A large, single-panel, frame, or assembly of panels on which are mounted, on the face, back, or both, switches, overcurrent and other protective devices, buses, and usually instruments. Switchboards are generally accessible from the rear as well as from the front, and are not intended to be installed in cabinets. (Adapted from the NEC.) (B) A metal-enclosed panel or assembly of panels that may contain molded case, insulated case, or power circuit breakers, bolted pressure contact or fusible switches, protective devices, and instruments. These devices may be mounted on the face or the back of the assembly. Switchboards are generally accessible from the rear as well as from the front; however, they can be front accessible only.

switchgear: (A) A general term covering switching and interrupting devices and their combination with associated control, instrumentation, metering, protective, and regulating devices and covering assemblies of these devices with associated interconnections, accessories, and supporting structures used primarily in connection with the generation, transmission, distribution, and conversion of electrical power. (B) An assembly of equipment used to switch and control electrical power.

tertiary winding: An additional winding in a transformer that can be connected to a synchronous condenser, a reactor, an auxiliary circuit, etc. For transformers with wye-connected primary and secondary windings, it may also help (1) to stabilize voltages to the neutral, when delta connected (2) to reduce the magnitude of third harmonics when delta connected (3) to control the value of the zero-sequence impedance (4) to serve load.

valve-regulated lead-acid (VRLA) cell: A lead-acid cell that is sealed with the exception of a valve that opens to the atmosphere when the internal pressure in the cell exceeds atmospheric pressure by a preselected

amount. VRLA cells provide a means for recombination of internally generated hydrogen and oxygen to limit water consumption.

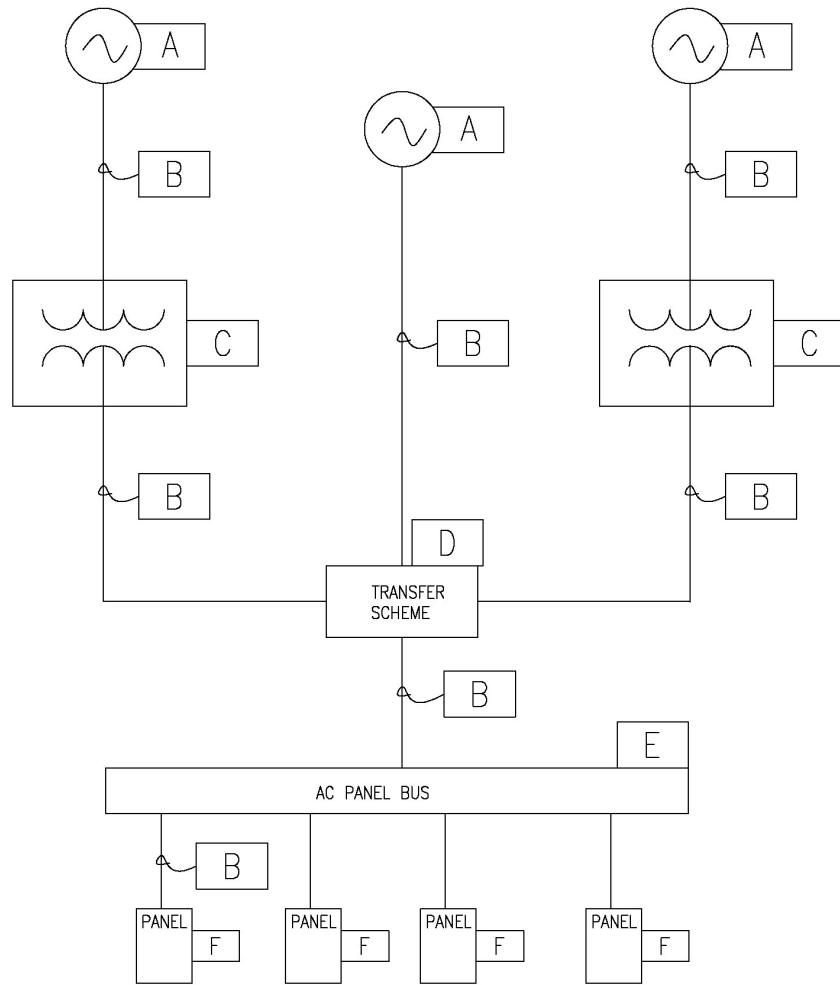
vented battery: A battery in which the products of electrolysis and evaporation are allowed to escape to the atmosphere as they are generated. These batteries are also commonly referred to as *flooded*.

4. Design of substation ac auxiliary systems

4.1 Introduction

The objective of this section is to provide the required information for the substation engineer to design an ac auxiliary system as applicable for a substation. Figure 1⁴ represents an ultimate station power configuration that can be applied to any substation depending on substation size, reliability, and load requirements. One ac source is designated as the normal or preferred source, and the second and third (if available or necessary) sources are designated as the backup source(s). A loss of the normal source may require transferring the load to a backup source. In substations with multiple sources, the sources are typically connected through a transferring scheme. One or more ac panels are used to serve the substation load as required.

⁴Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.



NOTE—The above letters reference different subsections covering specific components of ac auxiliary power schemes as follows: A: see 4.2, 4.3, and 4.4; B: see 4.5; C: see 4.6; D: see 4.7; E: see 4.8; F: see 4.9.

Figure 1—Block diagram for typical substation ac auxiliary power

In the first step of the design process, the design engineer should review:

- a) The design criteria for the station service.
- b) The number of station service sources available. The source type could be single-phase or three-phase.
- c) The load required to be served.

4.2 Design criteria

4.2.1 Introduction

In general, the design criteria of the ac auxiliary system are determined by the existing, proposed, and future substation loads, typically measured in kVA. Diversity of the total connected load needs to be considered as not all loads are concurrent. For example, the control enclosure cooling system should not run simultaneously with the heating system; redundant cooling systems are not concurrent; and spring charging motors for power circuit breakers may not run concurrently.

Also considered with the substation loads are the equipment voltage ratings and phase requirements (single- or three-phase) of the substation equipment to be installed. When sizing auxiliary transformers and other station power components, the designer should consider substation expansion and short-term loads, such as construction or maintenance loads. Timing of any proposed expansion may dictate initial installation or deferral of station power components. Some loads may be identified as critical, which requires ac service to be maintained continuously. Depending upon such critical loads, the substation may require two or three ac station service sources with the ability to transfer loads between sources.

Due to the importance of the station power to the operation and reliability of the substation, the following factors should be considered in order to determine the required station power configurations. This guide indicates various equipment ratings (voltage, ampacity, capacity, etc.) compliant with IEEE and NEMA standards. Equipment with other ratings conforming to standards published by other organizations is available. Design philosophies and practices presented in this guide should be adapted appropriately based on the equipment utilized in design and authority having jurisdiction.

4.2.2 System stability

System stability considerations are important for the reliability requirements of the station power. If the loss of a substation results in a system disturbance to the electrical grid that could create a blackout condition in the area, the station service system should have an independent power source. The auxiliary power system requirements for redundant supply may also need to include the ability for the station to complete black start operations—meaning a local generation source is required to supply the station power system and battery chargers for the protection circuits in the event of a system collapse and subsequent repowering. See 4.3.5 and 4.7.5.

4.2.3 Customer service and loss of revenue

Some substations serve critical loads such as hospitals, manufacturing complexes, government offices, schools, or serve large blocks of load where the substation reliability requirements are high. Some substations are connected to power plants that obtain at least a portion of their station service from the substation. Loss of the substation station service may result in tripping the plant and lead to a loss of revenue. These type of stations may need multiple station power sources. Other less critical substations may only have one station power source.

4.2.4 Equipment protection

Substation equipment protection considerations should be given to all substations regardless of the size. High-voltage and extra-high-voltage substations contain expensive equipment such as transformers where the cooling system is important for operation and a backup source is generally required. Similarly, protective relays or other electronic control equipment located in high-temperature areas may require a continuous cooling system and a second power source. Separately implemented control and protection schemes may be implemented to mitigate the likelihood of equipment damage. The control and protection schemes are outside the scope of this guide.

For neutral grounding, there are several different grounding philosophies. The designer should ground station service transformer neutrals per utility practice or local jurisdictional requirements.

4.2.5 Design considerations

The designer may consider the following list when designing an ac system for substations:

- a) Location of ac equipment—indoor or outdoor
- b) Number of ac panels
- c) Essential loads

- d) Non-essential loads
- e) Conductor types and sizes
- f) Voltage drop calculations
- g) Jurisdictional requirements such as the National Electrical Code® (NEC®) [B34]⁵
- h) Arc flash considerations

4.2.6 Selection of auxiliary system voltage

Several secondary voltage levels are available for ac auxiliary systems. When determining the secondary voltage, the designer may use a standard voltage level determined by the designer's power system or use a voltage level based on the supplied equipment. Either way, the designer should consider the factors listed in 4.4. Voltage ratings listed in this document are typical of North American power systems, but are not all inclusive. Variations to these voltages discussed in this document are common in other areas of the world.

4.3 Station power source requirements

4.3.1 Introduction

Three ac sources are represented in Figure 1. One source, typically the most reliable source, is designated as the primary, or normal, source. The second source is designated as the backup source and is used when the normal source is unavailable. The third source is used as a second backup and is utilized only when both the normal and secondary sources are unavailable.

There are four sources that are commonly used as substation ac auxiliary power sources:

- a) Power transformer tertiary
- b) Substation bus
- c) Distribution line
- d) Standby generators

Each source has advantages and disadvantages. Substation location, substation equipment, and bus configurations may dictate which source is normal. The selection of redundant sources is important so an outage would not remove both normal and alternate sources.

4.3.2 Power transformer tertiary

The tertiary of a power transformer in substations can provide a reliable source for station power applications. When the primary and secondary windings are connected wye, a third winding connected in delta is typically used for transformer stabilizing purposes. A tertiary winding presents a low impedance path for zero-sequence currents and harmonics, thereby reducing the zero-sequence impedance presented to the outside world, while avoiding the problem of tank heating. The tertiary winding typically has a volt-ampere rating between 20% to 30% of the volt-ampere rating of the primary winding. The tertiary winding typically has a medium-voltage rating up to 34.5 kV. If there are plans to use the transformer tertiary for station auxiliary power purposes, the tertiary winding is brought out of the transformer through bushings.

The volt-ampere rating of the tertiary winding typically exceeds the maximum volt-ampere requirement of a substation's ac auxiliary power load and is an adequate ac auxiliary power source.

⁵The numbers in brackets correspond to those of the bibliography in Annex A.

Consideration should be given to the available fault current at the tertiary bus. In the case that the fault current magnitude exceeds the interrupting rating of the protective equipment, such as fuses or circuit breakers, several options can be employed to mitigate the fault current. These options include installing current limiting fuses, resistors, or reactors; or increasing the transformer tertiary impedance.

4.3.3 Substation bus

The substation bus is another available source for auxiliary station power. When distribution voltage is available, distribution transformers are typically utilized for station service. Transmission voltage buses can be used, but are not typically preferred due to their relatively high cost. A station service voltage transformer (SSVT) is used to transform the transmission bus voltage to the ac auxiliary voltage. These transformers are available for voltages from 34.5 kV to 345 kV. One or more SSVTs might be required, depending on required station power load. See Figure 2 for possible connections.

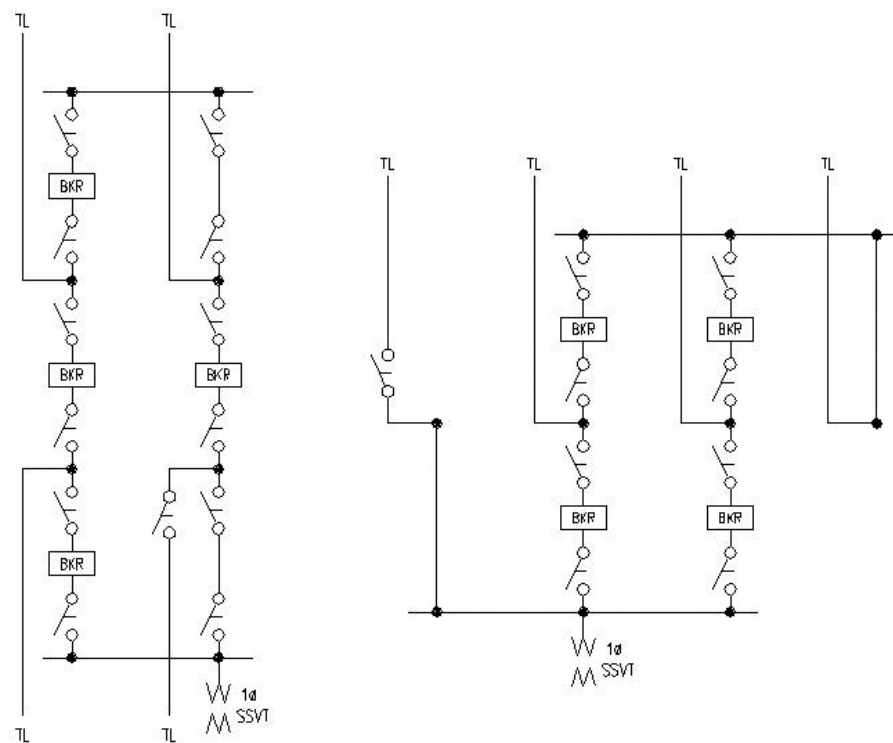


Figure 2—Possible SSVT locations

The SSVT is located within the line or bus zone of protection. A fault on the SSVT may be cleared by the protective relay or by a high-side fuse. Depending on the size of the SSVT, the required fuse ampacity may not be available for certain voltage levels. The protection engineer should be consulted for the final location when determining the required SSVT protection. Low-side overcurrent protection of the secondary conductors used for auxiliary station service are typically applied as close to the secondary terminals as possible. Surge protection is typically needed on the high-side connection of the SSVT. If arresters protecting other equipment in the station are close enough to protect the SSVT, a dedicated arrester for the SSVT may not be required. Guidance on surge protection and separation effects can be found in IEEE Std C62.22™ [B27].

4.3.4 Distribution feeders

A common source for substation auxiliary station power is the use of nearby distribution feeder circuits. The feeder primary is typically connected to a step-down transformer located near the control enclosure. If the feeder is owned by another utility, a revenue meter is installed. Since the feeder has more exposure to faults, it is typically used as a backup to the primary source.

4.3.5 Standby generators

Generators may also be used as an ac auxiliary power source. In substations, generators are typically used as an emergency/backup power source. There are many disadvantages in using generators as a permanent ac auxiliary source. Choosing to use generators as a permanent ac auxiliary source requires additional design considerations. When using generators, designers should consider fire-protection systems, fuel-storage systems, ventilation, and the climate. Generators may also be housed in a separate building structure, which requires the installation of a ventilation system. If the generators are located outdoors in the switchyard, there is a reduced need for fire-protection installation, fuel-storage systems, or building ventilation.

4.4 Load analysis

4.4.1 Introduction

In order to design a reliable station service system, the ac loads for the system need to be identified and calculated. The designer should consider the ultimate plan for the substation in order to account for future loads anticipated at the station. After the ac loads have been identified, the demand and load factors for each load should be applied. The resultant ac loads are used to size the station service transformer(s) and determine associated conductor ratings. The use of demand and load factors allow for the economical selection of the transformer size without being overly conservative.

4.4.2 Load identification

The following types of loads should be considered when identifying the overall station load:

- a) Substation major equipment loads, including:
 - 1) Transformer cooling fans
 - 2) Transformer pumps
 - 3) Load tap changer motor drives
 - 4) Breaker ac charging motors
 - 5) Equipment heaters
 - 6) Yard loads—This load includes yard lighting and receptacle loads for equipment testing. Also transformer oil-retention pit pumps load should be included.
- b) Control enclosure loads: The control enclosure houses critical equipment used for the protection and operation of the substation. This equipment includes substation protective relays, metering, battery chargers, and control equipment. For optimum operation of this equipment, the cooling and heating of the control enclosure should be operated within a specified temperature range. Other loads may include control enclosure lights and receptacle loads.
- c) Maintenance equipment load: For large substations, maintenance crews may elect to use a portable generator as a source for the maintenance equipment. If maintenance equipment is served from the station power transformer, the load of the maintenance equipment should be included.

- d) Ancillary structures: The substation may have additional structures for maintenance, storage, or other purposes. Include any heating, ventilation, and air conditioning (HVAC), equipment, or structure auxiliary load if it is sourced from the substation ac system.
- e) Future build out: In order to account for the ultimate load of the substation, any future loads should be considered and included in calculating the maximum station load. This includes loads for additional power transformers, cooling and heating, breakers, etc.

4.4.3 Equipment rating identification

Once all planned and future loads have been identified, the ratings for each load need to be established. Ratings may be provided by the equipment manufacturer in amperes, watts, or kVA. In order to calculate the station load, a common basis needs to be used. Either current or kVA are typically used because both are easy and straightforward. If current is used, the total power should be calculated based on the respective voltage class of the equipment. Loads also should be segregated between single-phase and three-phase. For multiple-phase systems, loads need to be balanced between phases for optimal transformer loading.

4.4.4 Demand and load factors

The demand factor is the ratio of the maximum coincident demand of a system, or part of a system, to the total load connected to the system, or part of the system, per IEEE Std 141™ [B3]:

$$\text{demand factor} = \frac{\text{maximum coincident system demand}}{\text{total load connected to the system}} \quad (1)$$

Demand factors can also be established for a subset of similar equipment (such as receptacles) rather than only a single system-level demand factor.

The second consideration is the amount of time that a load runs based on a selected period of time, referred to as *load factor*. Load factor is the ratio of the average load over a designated period of time to the peak load occurring in that period per IEEE Std 141 [B3]:

$$\text{load factor} = \frac{\text{average load over a designated time period}}{\text{peak load occurring in that period}} \quad (2)$$

The period for which the load factor is considered should be chosen based on the load capability of the transformer(s) that is used in the design. For best practice, loads operating for three hours or more should be considered as continuous load. High loads that operate for short periods of time also need special consideration in relation to the entire system load.

4.4.5 Load calculations

After equipment ratings have been established, the demand and load factors are selected. Selecting the demand and load factors often requires engineering judgment in terms of familiarity with substation operations and understanding how the loads such as receptacles, lighting, air conditioning, transformer cooling fans, etc., are applied. Applying the demand and load factors provides a more realistic adjusted load (rather than simply summing up the nameplate ratings of the equipment) for sizing of the station service transformers. In the process of determining the ultimate loading, various conditions (generally the worst case scenario) under which loads may be operated should be considered, such as seasonal and/or time of day. The person responsible for the sizing of the transformer can perform the total adjusted load calculations.

For information on the process of sizing transformers, see 4.6. Be aware that the thermal time constants (overload capability) of transformers are determined by the manufacturers and are typically different for

dry type and liquid-immersed units. Refer to IEEE Std C57.91™ [B24] and IEEE Std C57.96™ [B25] for additional information.

A general example of a substation load analysis is shown [Table 1](#). The example only considers the case of loads running during the daytime in the summer. It is not an exact or comprehensive analysis for substations, but intended to illustrate one practical approach to the process. Load analysis varies based on substation voltage class, capacity, climate, and any non-traditional loads.

In the example, adjusted kVA load (for transformer sizing) is determined as follows:

$$\text{adjusted kVA} = \text{quantity} \times \text{kVA per unit} \times \text{demand factor} \times \text{load factor} \quad (3)$$

Justification or reasoning for the demand and load factors should be documented, such as shown in the comments column of the example.

4.5 Conductor selection

4.5.1 Introduction

[Subclause 4.5](#) presents general information useful in the selection of both line and load conductors. It describes various characteristics essential to conductor selection: conductor type, insulation type, insulation voltage rating, insulation temperature rating, conductor terminations, and conductor size. An essential document in understanding ac and dc cables used in substation design is IEEE Std 525™.

A process flow chart has been developed to aid the designer/engineer in the conductor selection process. However, any rules and restrictions set forth by the authority having jurisdiction (AHJ) in the area that work is being performed supersede any documents referenced in this section.

This section covers the selection of both line and load conductors. There are six main characteristics to consider when selecting a conductor—conductor type, insulation type, cable insulation voltage rating, cable insulation temperature rating, the terminations being connected to (temperature rating, ampacity, etc.), and conductor size. The engineer performing the conductor selection can use the process flow chart shown in [Figure 3](#) and described in [4.5](#) for guidance on conductor selection based on these characteristics.

For specific examples on selecting conductors (control, instrument, power, and communication), refer to the annexes in the latest version of IEEE Std 525.

Table 1—Generic substation ac load study

Equipment type	Qty	Phase	Volts (ac)	Amps (each)	kW (each)	Power factor	kVA (each)	Load factor	Demand factor	Single-phase load (kVA)	Three-phase demand load (kVA)	Comments
Outdoor receptacles	4	1ø	120	15.00	1.530	0.85	1.800	1.000	0.25	1.80		Considering one in use at any given time.
Indoor receptacles	8	1ø	120	15.00	1.530	0.85	1.800	1.000	0.25	3.60		Considering two in use at any given time, more constant loads than outdoor (commissioning, etc.). Load factor is a median estimate for any connected equipment, which could run for two hours or more.
Outdoor lighting	10	1ø	120	1.67	0.170	0.85	0.200	1.000	0	0.00		Lights off during day.
Indoor building lights	20	1ø	208	1.20	0.213	0.85	0.250	1.000	1.000	5.00		Estimated load and demand factors are based on potential occupancy at any given time.
Basement lighting	70	1ø	120	0.21	0.021	0.85	0.025	1.000	1.000	1.75		Basement lights are typically only turned on as needed (maintenance, etc.), but could be on for extended periods of time, depending on the type of work being performed.
Roll-up door motor	2	3ø	208	3.27	1.000	0.85	1.176	0.000	1.000		0.00	One running at any given time, typically not running more than 15 s per operation (hence 0 load factor).
Exhaust fans	6	3ø	208	2.61	0.800	0.85	0.941	1.000	0.667		3.76	Estimated four running at any given time.
Fire alarm panel	2	1ø	120	4.17	0.500	1.00	0.500	1.000	1.000	1.00		Both running at all times.
3 HP battery room HVAC system	1	3ø	208	7.31	2.238	0.85	2.633	1.000	1.000		2.63	Load factor depends on requirements (ambient conditions for chargers, etc.). In this case, it is assumed that the load is constant for three hours or more.

Table continues

Table 1—Generic substation ac load study (continued)

Equipment type	Qty	Phase	Volts (ac)	Amps (each)	kW (each)	Power factor	kVA (each)	Load factor	Demand factor	Single-phase load (kVA)	Three-phase demand load (kVA)	Comments
Battery charger	2	3ø	208	53.00	17.164	0.90	19.072	1.000	1.000		38.14	Based on the situation of having a dc system outage that completely drains the batteries, requiring full restoration upon re-energization. Both chargers would run at maximum output until the batteries have recharged, which could be over three hours, depending on the battery system.
9 kW control building HVAC	1	3ø	208	29.39	9.000	0.85	10.588	1.000	1.000		10.59	Assumed worst case summer load.
Receptacles—rack service/maintenance (10-receptacle power strip)	30	1ø	120	15.00	1.530	0.85	1.800	0.500	0.133	3.60		Assumed four used at any given time. Load factor is a median estimate for any connected equipment, which could run for two hours or more.
Communication rack power strip (10 receptacle)	1	1ø	120	15.00	1.530	0.85	1.800	0.300	0.500	0.27		Though there are ten receptacles, typically, no more than two or three are used at a time for smaller loads (laptops, test equipment, etc.). Those small loads require less than half the available ampacity of any given receptacle. Rough estimate of 180 VA per receptacle used here.
420 MVA transformer auxiliary power supply	1	3ø	208	50.00	16.193	0.90	17.992	1.000	1.000		17.99	Only one transformer. Loads mostly consist of fans, pumps, etc., which are considered to be running for at least three hours.
1ø and 3ø kVA totals												
Total kVA										17.02	73.12	
											90.14	

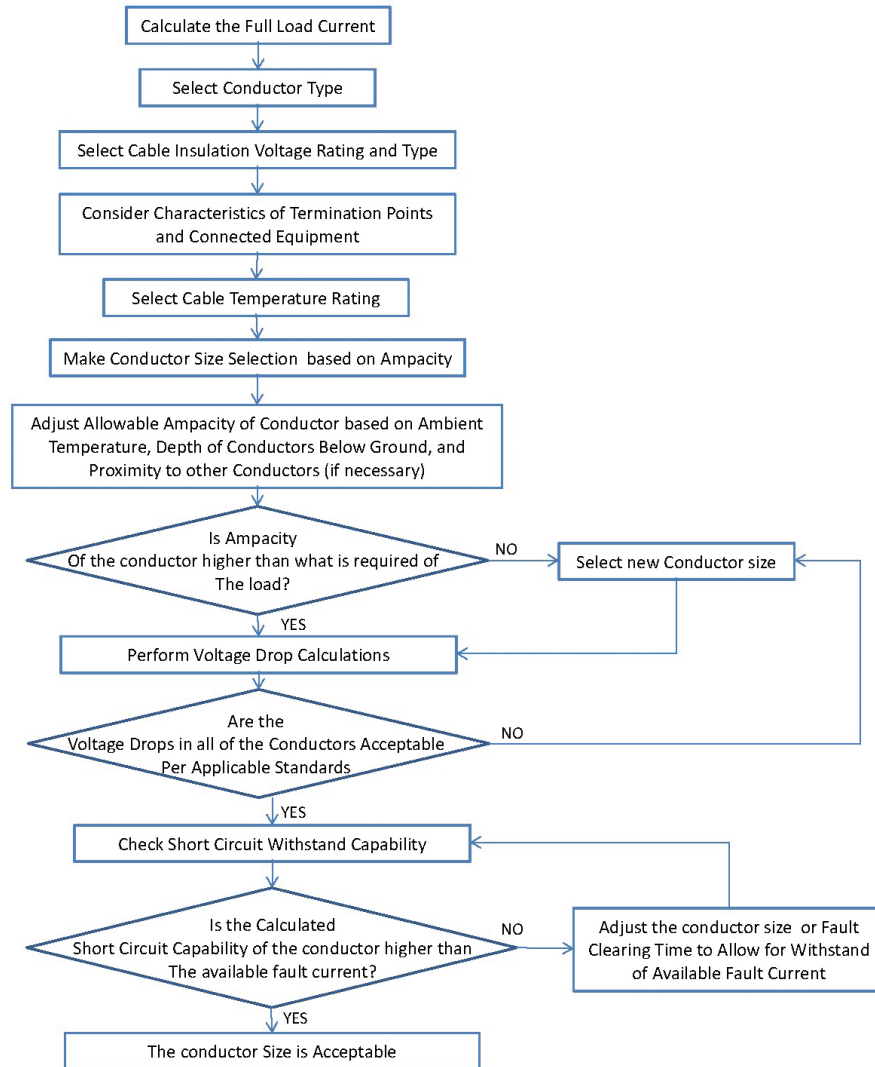


Figure 3—Conductor selection process flow chart

4.5.2 Conductor type

The first step in conductor selection is to determine the type of conductor to be used. The conductor material and stranding type are the most important factors to consider (i.e., aluminum versus copper and stranded versus solid). There are advantages to using each type of conductor depending on the application. Consider characteristics such as their weight, conductivity, and surrounding environmental conditions for the application of the conductors. Copper has historically been used for conductors of insulated cables due to its desirable electrical and mechanical properties. The need for mechanical flexibility usually determines whether a solid or a stranded conductor is used, and the degree of flexibility is a function of the total number of strands. A single insulated or bare wire is defined as a conductor, whereas an assembly of two or more insulated conductors, with or without an overall covering, is defined as a cable. All of this information is typically available from the cable manufacturer. For additional information on conductor material and stranding, see IEEE Std 141 [B3] and IEEE Std 525.

4.5.3 Cable insulation voltage rating

Cable insulation voltage rating is selected based on the operating voltage, and the expected fault-clearing time. Further guidance on selecting the voltage rating of cables should be provided by the AHJ, or by specific product literature provided by the manufacturer.

4.5.4 Cable insulation type

For jacketed conductors, the insulation type should be selected to meet the local environmental conditions—such as dry, wet, or both, and chemical resistance. Typically, information on the application of different insulation types is available from the manufacturer. There may also be requirements by the AHJ. IEEE Std 141 [B3] and IEEE Std 525 provides general guidance on cable insulation selection.

4.5.5 Cable temperature rating

The temperature rating of the cable should be selected to withstand the ambient temperature of the environment in which it is installed, in addition to any self-heating that may occur. The designer selecting the conductor should note that the conductor installation may cross multiple environments, all of which should be considered. Typical conductor temperature ratings are 60 °C, 75 °C, 90 °C, and 105 °C.

4.5.6 Consideration for the characteristics of termination points and connected equipment

The ampacity of a conductor with a given temperature rating may need to be reduced depending on the type of termination points to which the conductor is connected. The conductor should not be allowed to become hotter than the thermal rating of the interconnected equipment. Typical equipment terminals are limited by the manufacturer to 75 °C. For an example involving cable selection based on termination ratings, see [Annex B](#).

4.5.7 Conductor size calculations

4.5.7.1 Introduction

The following factors should be considered when selecting the conductor size:

- a) Required ampacity (initial conductor size selection)
- b) Temperature, burial depth, and bundling corrections
- c) Voltage drop
- d) Short-circuit calculations

4.5.7.2 Required ampacity (initial conductor size selection)

All conductors should be initially sized based on the ampacity of the load(s) they are supplying. The size of the conductor may be based on requirements provided by the AHJ, or by specific product literature provided by the manufacturer. For an example involving the initial conductor size selection, reference [Annex B](#). Once the initial conductor type and size selection is made, verify the conductor has been sized to avoid overheating and excessive voltage drop. If the verifications prove the conductor size to be inadequate, then the engineer should make an economically and practically sound decision to redesign the load-distribution scheme. The redesign decision could involve any of the following options:

- a) Resize the conductor (reduces voltage drop)
- b) Reallocate loads to, or rebalance loads among, different circuits to adjust load distribution
- c) Add additional circuits to accommodate new loads (may require a larger ac panel)
- d) Decrease the distance of circuit run (reduces voltage drop)

- e) Consider a higher voltage distribution system and local step-down transformers

4.5.7.3 Temperature, burial depth, and bundling corrections

The ampacity rating of a cable may vary based on ambient temperature, burial depth, and proximity to other current-carrying conductors. The manufacturer can provide ampacity ratings based on a range of ambient temperatures. If the ambient temperature in the area of a particular cable installation is not within range of the ambient temperature specified by the manufacturer, then the ampacity should be adjusted. Guidance for this type of ampacity adjustment factor should be obtained from the cable manufacturer or the AHJ. For an example involving ampacity adjustment based on ambient temperature, see [B.2](#).

4.5.7.4 Voltage drop verifications

Losses by means of voltage drop across a conductor are directly proportional to the length and impedance of the conductor. Per Ohm's law, the higher the current a conductor is carrying, or the higher the resistance of a conductor, the greater the voltage drop. Voltage drop can create under-voltage issues for substation equipment, leading to various malfunctions, depending on the type of equipment.

Voltage drop calculation for a single-phase circuit:

$$\%V_D = \frac{2 \times I \times L \times [R \times pf + X \times \sin(\arccos(pf))]}{V} \times 100 \quad (4)$$

Voltage drop calculation for a 3-Ø load:

$$\%V_D = \frac{I \times L \times \sqrt{3} \times [R \times pf + X \times \sin(\arccos(pf))]}{V} \times 100 \quad (5)$$

where

V_D is the line-to-neutral voltage drop of the conductor expressed in volts, for a 1Ø conductor or the line-to-line voltage drop of the conductor expressed in volts for a 3Ø conductor
 V is the nominal voltage of the circuit
 R is the alternating-current resistance in ohms to neutral per unit measurement
 X is the alternating-current reactance in ohms to neutral per unit measurement
 I is the load in amperes at 100%
 L is the length of the conductor in unit measurement being considered for the voltage drop
 pf is the equivalent power factor being considered for the circuit. If this factor has been accounted for in the load study, then a value of 1.0 should be used in the voltage drop calculation

After a conductor size is selected with an acceptable level of voltage drop, verify the terminal voltage delivered compared to the operating voltage range of the load. It is important that adequate voltage is delivered to critical loads (i.e., trip coils, battery chargers, etc.). It is common for the AHJ to provide standards that provide acceptable levels of voltage drop. For an example involving voltage drop calculations, see [B.2](#).

4.5.7.5 Short-circuit calculations

Verify the conductor size can withstand the available short-circuit current at its termination point. Sizing of the conductor based on available fault current is a function of initial or continuous conductor operating temperature, the final conductor temperature after a fault, the maximum possible fault-clearing time based on protective devices, and available fault current at the circuit's termination point. The conductor final temperature limits should be obtained from the cable manufacturer. Suggested methods and values for sizing a conductor based on short-circuit current can be found in IEEE Std 525 and IEEE Std 242™ [\[B4\]](#). However,