



IEEE Design Guide for Electric Power Service Systems for Generating Stations

IEEE Power Engineering Society

Sponsored by the
Energy Development and Power Generation Committee



666TM

IEEE
3 Park Avenue
New York, NY 10016-5997, USA

4 May 2007

IEEE Std 666TM-2007
(Revision of
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**Energy Development and Power Generation Committee
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IEEE Power Engineering Society**

Approved 22 March 2007

IEEE-SA Standards Board

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Abstract: This guide applies to station service systems that supply electric power to auxiliary loads for electric power generating stations. The discussions and recommendations in this guide provide the practices, criteria, and range of system parameters that relate to the service system requirements and assist in the application of existing engineering documents. This guide is not a handbook of design data; however, it explains what is good practice for the many different types of electric power service systems for generating stations.

Keywords: auxiliary systems, cable, motor, relay, short circuit, transformer, voltage

The Institute of Electrical and Electronics Engineers, Inc.
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Print: ISBN 0-7381-4986-1 SH95547
PDF: ISBN 0-7381-4987-X SS95547

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Introduction

This introduction is not part of IEEE Std 666-2007, IEEE Design Guide for Electric Power Service Systems for Generating Stations.

This guide is primarily tutorial in nature as it is intended to provide guidance in the design of electric power service systems for electric power generation plants. The guidance and direction given in this guide is, for the most part, general in nature and is applicable to all types and sizes of electric power generating plants.

This guide does not provide unique and specific design direction and guidance for special systems in the various types of electric power generating plants, but rather provides the basic framework upon which any required unique and specific designs can be built. An electric power service system consists of a main auxiliary power distribution network, which may supply many subsystems such as electric trace heating systems, dc systems, Class 1E power systems, etc. It is recommended that the reader consult industry standards that address these specific subsystems in more detail as appropriate during the design process.

This design guide was prepared by the Working Group on Auxiliary Systems, which is part of the Station Design Subcommittee of the Energy Development and Power Generation Committee of the IEEE Power Engineering Society.

This revision includes primarily editorial changes needed to maintain consistency with phraseology and terminology changes that have been made in other referenced standards and documents and to correct typographical errors in the 1991 edition of this guide. It also includes only relatively minor technical changes.

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IEEE Design Guide for Electric Power Service Systems for Generating Stations

1. Overview

This design guide applies to station service systems that supply electric power to auxiliary loads for generating stations that produce electric power.

There are numerous industry standards, regulations, and guides for equipment and components of these systems. The discussions and recommendations contained herein provide the practices, criteria, and range of system parameters that relate to the service system requirements and assist in the application of the existing engineering documents.

This design guide is not a handbook of design data, but it explains what good practice is for the many different types of electric power service systems for generating stations. It is anticipated that this guide will assist those who establish the criteria for the design of generating station auxiliary loads and their electric power service.

2. Scope

While this design guide applies to all types of power generating stations, it is particularly applicable to stations in which the electric power service system is required to perform continuously. When electric power for auxiliary loads is supplied from the power grid, the service system begins at the point where the tap from the power grid terminates, either at a station service bus or at the terminals of the transformer that supplies the bus.

When service to auxiliary loads is from independent generators or electric storage batteries that are not normally operated as power supplies to the power grid, the station service system includes the generators and storage batteries. The service system includes all of the electric power using devices it serves, such as motors, resistance heaters, rectifiers, etc.

This guide contains a listing of typical power plant auxiliary loads and criteria for their power service and examples of single-line diagrams for a typical plant. It also includes tables of typical power service parameters to illustrate the range of typical values for each parameter, and it identifies the approximate effect of the minimum and maximum value of each parameter on the load. Each clause, as appropriate, has a bibliography of [U.S.](#) industry codes and standards and other reference documents that provide detailed guidance in the design and specification of station service system components.

3. System philosophy

3.1 General

An electric power generating station can only produce power if its auxiliary loads are functioning. Upon loss of supply power to these auxiliary loads, a unit may be idled or damaged. The electric power supply system for auxiliary loads generally costs less than 5% to 10% of the total plant cost. Additional costs incurred during a long-term outage due to nonproductive investment, repair of major equipment, and incremental cost of replacement power can exceed the total cost of the auxiliary system.

Power system engineers who plan and design an auxiliary system must be aware of the need for a well planned, well engineered, and reliable auxiliary system. They must consider a wide range of technical points during the planning process while using operating experiences and field reports, either acquired personally or by those who will eventually operate the system, to ensure that all possible aspects of the design have received attention. In this clause, basic design considerations (see 3.2), a general planning guide (see 3.3), and transmission system and main generation considerations (see 3.4) are presented to assist the engineer in planning and designing the auxiliary system.

This clause is devoted to the more basic and general philosophies that should be addressed in the design of an electric power service system. Expansion on these philosophies is undertaken in subsequent clauses that provide more detailed guidance on issues such as

- a) Typical power plant auxiliary loads and their power service requirements
- b) Typical power service parameters including how and why they should be considered
- c) Typical power service components and their design requirements
- d) Typical power system design requirements and limitations

3.2 Basic design considerations

Many factors are considered in the overall planning and design of an auxiliary system for a generating station. These factors influence the design and operation of a [generating](#) unit and may be stated as design criteria. Some of the factors are discussed in the following paragraphs. Where appropriate, examples of design criteria are given. It should be noted that some of the criteria overlap. A safety criterion, for example, may also be an equipment application criterion. Thus, the example criteria given may be classified differently by different designers. In all cases, a number of criteria should be developed. The criteria given below are merely examples and are not intended to be all inclusive.

3.2.1 Safety

Safety is of primary importance in the design of an auxiliary power supply system. Industry standards and codes for equipment capabilities should be met. Whereas the safety and design life of the equipment may be compromised under certain conditions, the possibility of harm to plant personnel and the public must be considered and avoided.

Safety considerations are implemented by establishing criteria such as the following:

- a) When all generating units are out of service, power is to be maintained for lighting, communication, heating, ventilation, control power, elevators, lubrication, plant security, and like loads for safe shutdown of the unit under normal and emergency conditions. This may be done by uninterruptible power ~~systems~~ [supplies \(UPSs\)](#) or other alternate ac or dc sources, depending upon the critical nature of the load.

- b) Power supplies and critical loads should be divided between unit auxiliary buses so that the failure of any one bus or power supply will not prevent the safe shutdown of the unit.
- c) All electrical equipment enclosures should be permanently grounded by direct connection to the station grounding system.

3.2.2 Reliability

Since the unit will not function without adequate auxiliary loads, the reliability of the auxiliary system directly affects plant performance. Interruptions that reduce the output of a unit, either partially or completely, should be avoided where possible. The system should be designed so that reserve capacity and alternative power supplies minimize the effects of service component outage. System design should minimize the effects of service component failures or malfunctions on the uninterrupted portion of the system.

The following are examples of possible reliability design criteria:

- a) The failure of one start-up source should not prevent any unit from being started or shut down.
- b) Any unit should be able to carry a full load with one of its unit auxiliary transformers out of service.

The reliability of the auxiliary power supply system should be consistent with the importance of the unit to the power system, [contractual requirements, warranty considerations, overall costs](#), industry codes and standards, and regulatory requirements.

3.2.3 Cost

Capital operating and maintenance costs of the auxiliary power supply system and associated equipment are key factors in the design. Costs for installation, operation, expandability, and maintenance should be evaluated over the life of the equipment as part of determining the total cost of each plan. Although the worth of expandability and future capability of the system is usually difficult to quantify, it is very important because future load additions may require expensive modifications that may be avoided or minimized by considering them properly in the initial design.

3.2.4 Operation

Auxiliary power-supply systems that are flexible and simple to operate can contribute greatly to system reliability. Direct radial systems are simple. However, designing for additional reliability can suggest interconnecting buses or providing ties between buses. Interconnecting auxiliary buses usually results in a complex switching scheme that may be difficult or expensive to protect. Ties between buses may result in switching errors that cause equipment damage or unit trips.

Since designing for additional reliability often results in a more complex system, the operation of these systems should be considered to determine the true increase in reliability.

The following are examples of operating criteria for reliable designs:

- a) The unit will normally provide power for its auxiliary loads through transformers connected to the generator bus.
- b) The protective relaying will function to isolate system faults by removing a minimum number of components from service.

3.2.5 Equipment application

Equipment selection and application within an auxiliary system are subject to a number of industry application guides, manufacturing standards, and safety standards. To assure safe, economical, and dependable operation, the equipment should be applied in accordance with the recommendations of the appropriate guides and standards. As many of the major pieces of equipment used in the auxiliary system are expensive, the application and protection of the equipment should be coordinated. The following are examples of design criteria that apply to equipment application:

- a) The auxiliary power system steady-state voltage regulation should not exceed industry standards.
- b) Voltage dip when starting any large motor should not prevent the motor from starting or damage the motor.
This voltage dip should not cause malfunction of energized loads, such as stalling of running motors, or cause dropout of relays or contactors.
- c) The transformer impedances should be coordinated with the switchgear ratings. Fault currents should be determined with maximum loads, maximum transformer primary voltages, and minimum source impedances while assuming negative manufacturer's tolerances on impedances.
- d) The horsepower rating of the motors should be coordinated with the requirements of the driven load (see Clause 11).
- e) Any motor, NEMA frame size 440 or larger, should be capable of accelerating its load with 85% of rated motor nameplate voltage at the motor terminals (see ANSI C50.41 [B1]¹). This criterion can be more restrictive than criterion b) of this subclause. An alternate criterion might specify that these motors be capable of accelerating their loads with less than 85% rated voltage applied, thus allowing more flexibility in specifying parameters such as transformer impedances.
- f) [The harmonic content of bus voltages and of currents flowing through transformers and cables should be within industry standards or analyzed and considered in the equipment specification.](#)

3.2.6 Maintenance

The design of the auxiliary power supply system should include provisions for preventive maintenance. The equipment should be located so that it is accessible for inspection, removal, teardown, and repair, and the work space should be well lighted, adequately ventilated, and safe for personnel. In some cases, additional power circuits or components may be desirable to provide back-up service to certain auxiliary loads that permit in-service repairs without reducing unit output. This could be expressed as one of the design criteria given in 3.2.2. A cost/benefit analysis of this form of service should be made during the design of the auxiliary power supply system.

3.2.7 Plant expansion

Over the life of a plant, loads may be added for environmental protection, improvements in plant efficiency, safety, reliability, and other changes in operating conditions. These future loads should be anticipated during the initial design, though their details may not be known. Some designers may choose to build as large a system as is feasible to maximize reserve capacity (i.e., transformers are sized to the maximum short-circuit and voltage-regulation limits). An alternate design would provide for future switchgear, transformers, and other equipment that might be required.

The following are examples of design criteria for plant expansion:

- a) The overall design should provide for flue gas desulfurization equipment.
- b) The unit auxiliary and station service transformers should have a specified reserve capability.

- c) The unit auxiliary and station service transformers should have provisions for future forced-cooled ratings.
- d) A specified number of spare switchgear cubicles should be provided.
- e) Space should be provided in the physical design for connection of future transformers to the generator and startup source overhead conductors.

¹The numbers in brackets correspond to the numbers of the bibliography in 3.5.

Approaches may vary, but the planner is encouraged to make allowances for expansion, which, as history indicates, is inevitable. Where economics dictates a minimal initial system, the design should include physical space to accommodate some expansion without major difficulty.

3.3 General planning guide

There are many general system considerations, concepts, design principles, and operating philosophies that, if evaluated during the planning stage, can result in a more reliable, flexible, and economical auxiliary system. Some major factors to be evaluated are discussed in 3.2. In this subclause, these factors are discussed in more detail as they apply specifically to auxiliary system planning. A planning guide flow chart is presented in Figure 3.1. Many of the items included will not be applicable to particular units; however, some apply to all plants. Where experience or other factors dictate, the planning guide should be modified.

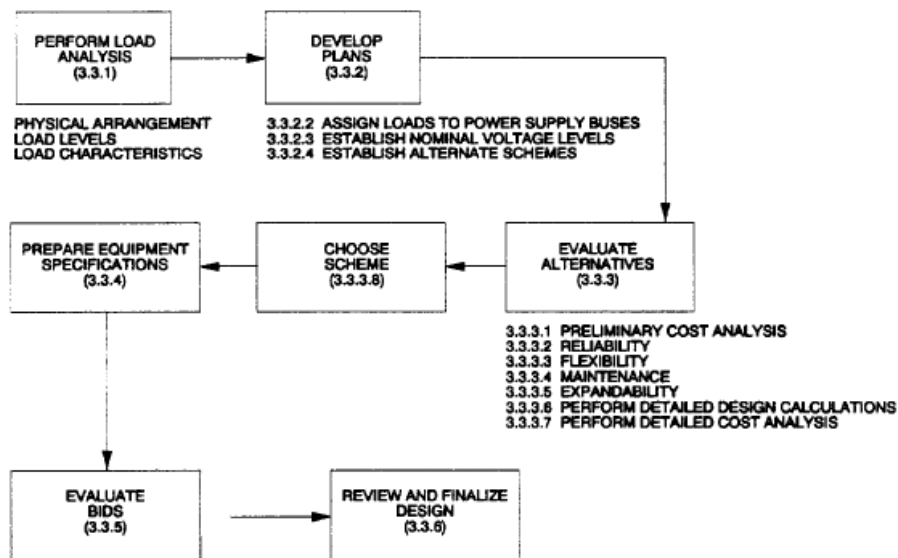


Figure 3.1—Planning guide flow chart

3.3.1 Load analysis

An initial step in the design of a power supply system is the analysis of the auxiliary loads to be served. The electrical system that serves these auxiliary loads should have capacity and availability equal to their functional requirements. During the initial design stages, firm data on the auxiliary loads may be difficult to obtain. In these cases, estimates based on previous designs may be used. The load analysis should evaluate the following:

- a) *Physical arrangement.* Data on cable lengths, special load requirements, and alternative locations for auxiliary load buses and equipment.

- b) *Load levels.* Data such as the horsepower, power factor, and demand factor of the load should be obtained to determine capacity ratings of power supply circuits and equipment.
- c) *Load characteristics.* How the loads can and will be operated can influence the auxiliary system design (i.e., low speed start of two-speed motors, number of required switching operations, required startup loads, running and shutdown loads, variable frequency drive system harmonics, etc.)

Additional details of load analysis are presented in Clause 4.

3.3.2 Development of plans

3.3.2.1 General

All acceptable plans or schemes should be developed within the established design criteria. No one plan may completely satisfy all design criteria at a reasonable cost. An optimal plan, however, can be found. This plan should consider the following criteria as well as the design criteria.

- a) *Operating experience.* Examination of design and operating experience on existing plants will provide useful information in establishing acceptable plans for the auxiliary power system. Information on the performance of past designs can be used to avoid the pitfalls of designs that have performed less than satisfactorily. Data on past operating experience can provide information on expected load demand factors, desired bus voltage regulation (which may be more restrictive than equipment limits), special switching features, etc.
- b) *Accepted industry standards.* The schemes to be evaluated should conform to accepted industry standards. This provides some correlation between the auxiliary power system designer and the equipment manufacturer. Industry standards can be obtained from the American National Standards Institute (ANSI), the Institute of Electrical and Electronics Engineers (IEEE), the National Electrical Manufacturers Association (NEMA), and other technical or environmental organizations.

3.3.2.2 Assigning loads to buses

In assigning loads to buses, the following criteria apply:

- a) Multiple loads providing the same function for a unit (e.g., multiple induced-draft fans) should have separate power circuits and should be supplied from a minimum of two buses. This will enhance the possibility of being able to operate the plant (even at reduced output), or minimize mechanical system transients due to the outage or trip of any one ~~power and short circuit or~~ auxiliary bus.
- b) The thermal and short-circuit loading on buses should be balanced to the extent practical to simplify certain equipment design, to minimize the number of different equipment ratings, to reduce system losses, etc.
- c) The large motor loads should be distributed onto multiple buses to reduce the motor contribution of fault current on any one bus. This allows better balancing of the bus fault levels. In addition, there may be economic advantages in having the larger motors on one power circuit or bus, so that lower rated switchgear can be used for the remaining power circuits and buses.
- d) Special purpose critical loads should be served by power circuits and buses having two separate and independent power supplies. The physical location of these load feeders also influences the overall bus and load configuration to assure that the failure of any one power-supply circuit will not cause the failure of other power supply circuits.
- e) Distribute harmonic generators, such as variable frequency drive systems, to reduce harmonic distortion on any one bus. Note that the effect of harmonic voltage and current distortion on system components (i.e., connected motors, relaying, meters, controls, generators, etc.) should also be considered.

These and other criteria are discussed in more detail in subsequent clauses.

3.3.2.3 Establishing nominal voltage levels

Various nominal voltage levels are evaluated during the auxiliary system planning phase to identify the best plan. Some of the factors evaluated in this analysis are

- a) Total bus loads
- b) Required short-circuit duty
- c) Steady-state voltage regulation
- d) Motor starting voltage dips
- e) Economics
- f) Cable sizing

These factors are interrelated and will be discussed in more detail in subsequent clauses.

3.3.2.4 Establishing alternate schemes

A number of schemes may be found acceptable in planning for any single auxiliary power system. Typical schemes are discussed below to illustrate variations.

²~~American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.~~

³~~Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.~~

⁴~~National Electrical Manufacturers Association, 2101 L Street NW, Washington, DC 20037, USA.~~

3.3.2.4.1 Nomenclature

A simplified single-line diagram of major components for a typical auxiliary power system is shown in Figure 3.2 as a reference for nomenclature used in the remaining figures. The auxiliary power system shown in Figure 3.2 receives its power from two sources: the unit source and the station source. The unit auxiliary buses primary power supply is through a unit auxiliary transformer (UAT) that connects via a tap to the generator bus between the generator circuit breaker and the unit transformer (UT). [Some generating facilities refer to the UT as the generator step-up. The two terms are synonymous for the purpose of this guide.](#) The unit must also have a supply of power for startup. This is supplied via the station service (startup) transformer (SST) or the UT, if a generator breaker is used. This startup source also may be used as a standby or spare power source and sometimes may be used to supply station auxiliary loads during unusual running conditions. The primary of the SST is connected to the high-voltage power system at a point that can be electrically close to or remote from the UT high-voltage connection.

The nominal voltage ratings of the auxiliary buses are usually 2.4 kV, 4.16 kV, 6.9 kV, or 13.8 kV. These voltage levels are referred to as medium voltage. A line-up of metal-clad switchgear forms each auxiliary (medium-voltage) bus, with individual circuit breakers feeding each of the large motors and/or unit substations or load centers. Sometimes fused contactors or fused load-break switches are used for individual feeders. [When using fused contactors, special care should be taken in coordinating the protective device selectivity for downstream relays that must coordinate with the fuse. In some cases, the maximum operating voltage for fused contactors is rated for lower maximum operating voltages than circuit breakers. This should be considered in the overall system design.](#)

Unit substations typically consist of a step-down transformer, a bus, and circuit breakers as an integral unit. A load center consists of the same components, but it may not be an integral unit and is therefore a more general term. The nominal voltage rating of the unit substations or load centers is usually 480 V or 600 V. Large low-voltage motors and motor control centers are individually connected to the unit substation through circuit breakers. Motor control centers supply small motors and other loads through combination starters and molded-case circuit breakers. The motor control center will have a supply breaker at the unit substation. The main breaker at the motor control center is optional. This optional breaker is usually justified when the motor control center is physically remote from the unit substation, because it may be desirable or required to have a local

device to disconnect the source for safety during maintenance [or when required by codes](#).

Other nomenclature will be defined as new equipment is introduced during discussions of other schemes.

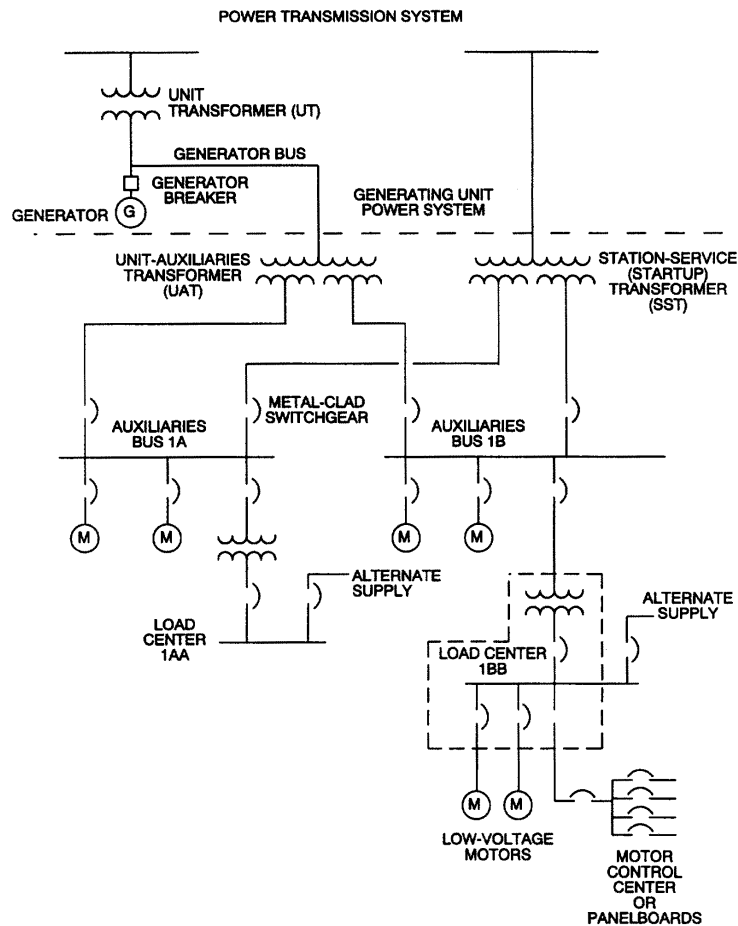


Figure 3.2—Simplified single-line diagram for unit connected power system

3.3.2.4.2 Typical scheme

After establishing the design criteria, analyzing the load to be served, and establishing acceptable nominal voltage levels, the designer can develop the single-line diagrams. A typical system for an 880 MW coal-fired unit is shown in Figure 3.3 and Figure 3.4. This system is a four bus, unit connected, power supply system. Note that the unit auxiliary buses are divided into two sets of duplicate buses, with each set of buses being supplied from a different UAT. The duplication of loads, which are segregated to different buses and different UATs, may avert an extended unit outage upon loss of any one bus or UAT. Figure 3.4 is an extension of Figure 3.3 and gives the details of the 480 V system, which is also arranged with reliability in mind. Additional reliability may be provided at either the 4.16 kV or the 480 V level by providing alternate supplies to these buses.

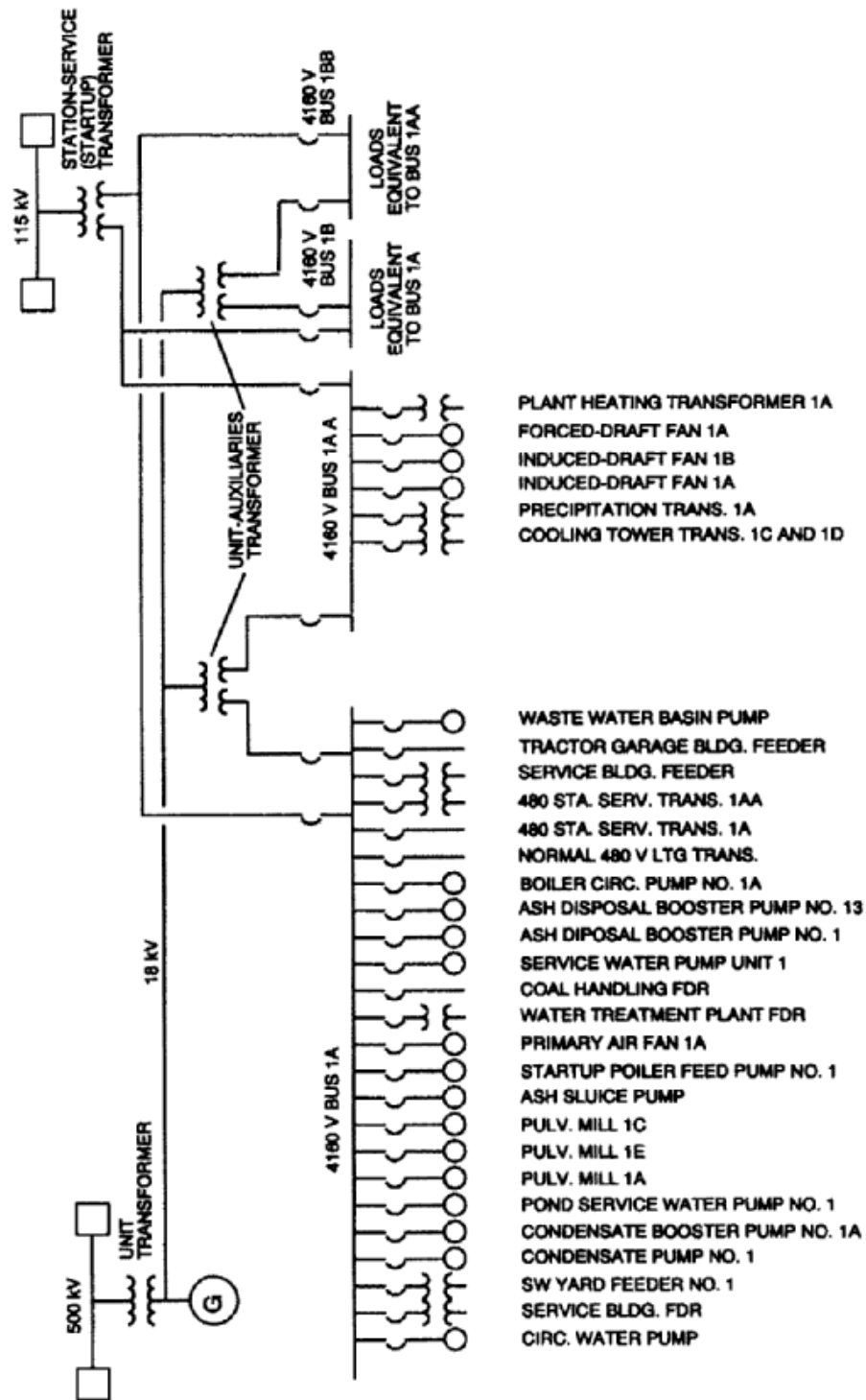


Figure 3.3—Expanded single-line diagram for 880 MW coal-fired unit

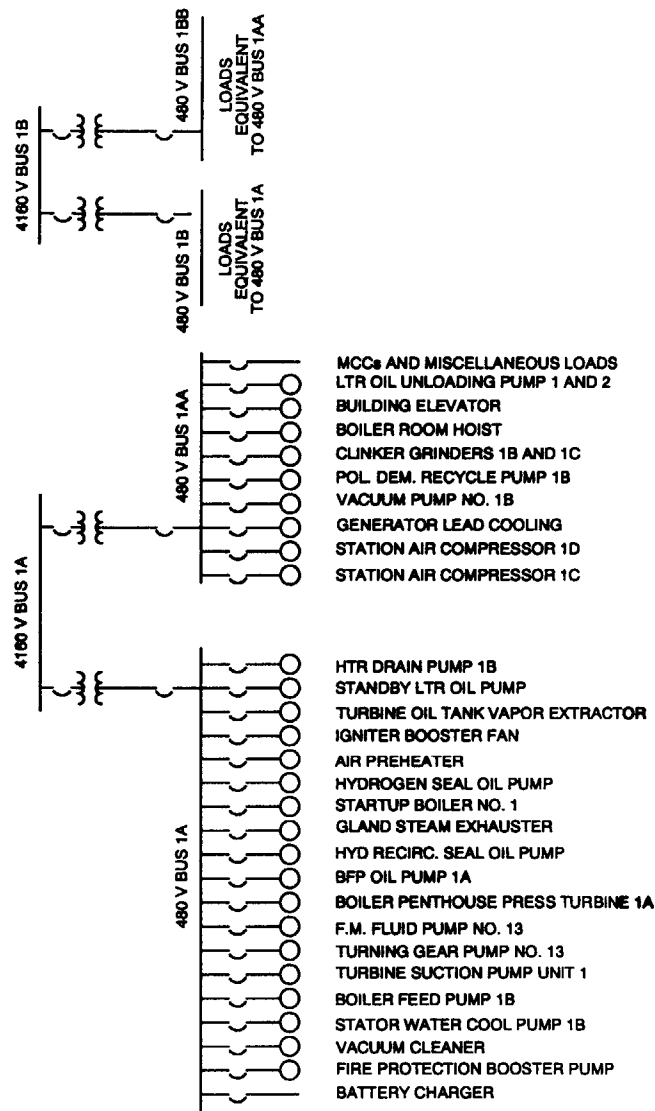


Figure 3.4—Expanded single-line diagram of the 880 MW coal-fired unit

3.3.2.4.3 Station service (startup) transformer (SST) connections

The connection of an SST is an input to the determination of the transmission substation bus arrangement. However, it is rare that this input would change the basic transmission bus arrangement (i.e., straight bus to ring bus). This bus arrangement is determined primarily by the transmission planning engineer to satisfy utility power system stability, reliability, operation, maintenance, and cost. Figure 3.5 through Figure 3.10 illustrate the most common connections; however, other arrangements and variations do exist.

- Figure 3.5 shows a straight bus. This may be the simplest of all arrangements. It offers relaying simplicity and cost savings at reduced reliability. Any line fault with breaker failure, or any bus fault, will result in interruption of station and transmission line service [and total loss of ac to the plant](#).

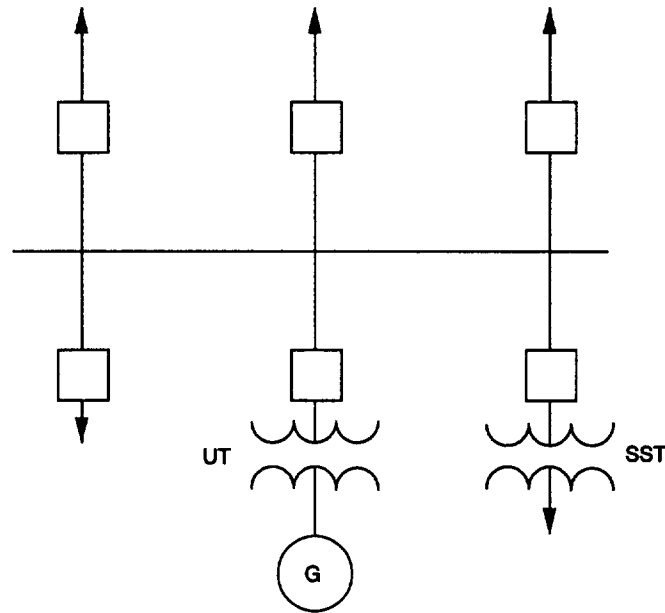


Figure 3.5—Straight bus

b) Figure 3.6 shows a main and transfer bus. For this arrangement, the SST is connected directly to the transmission bus. Any fault on an adjacent bus section or line with a failed circuit breaker results in loss of power to the SST. An alternative connection might have a breaker for the SST to remove a faulted SST from the bus.

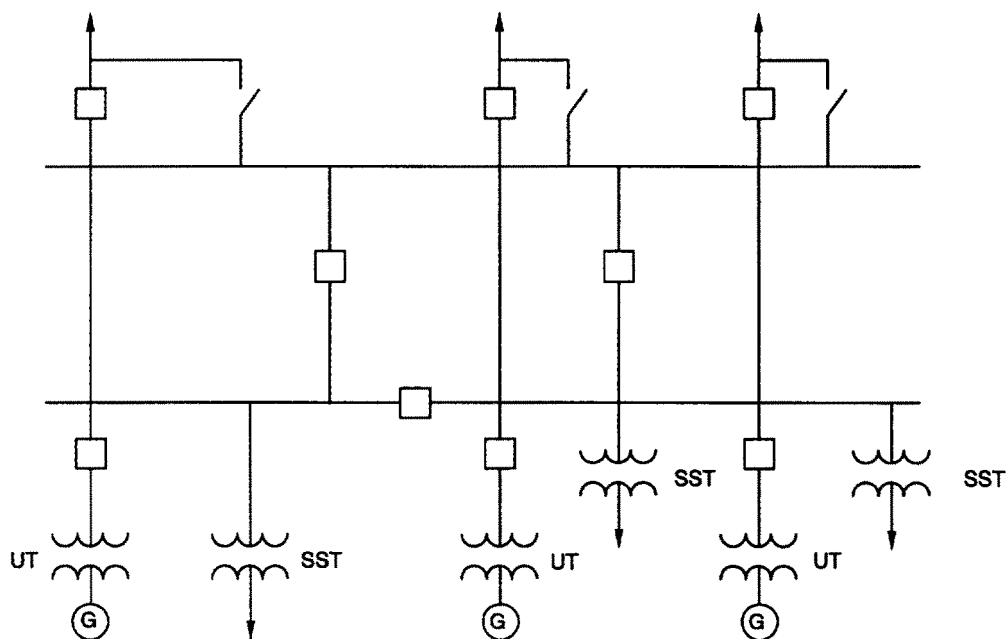
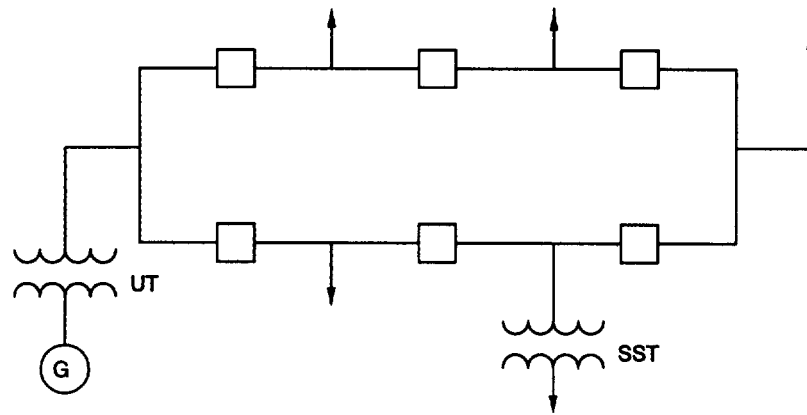


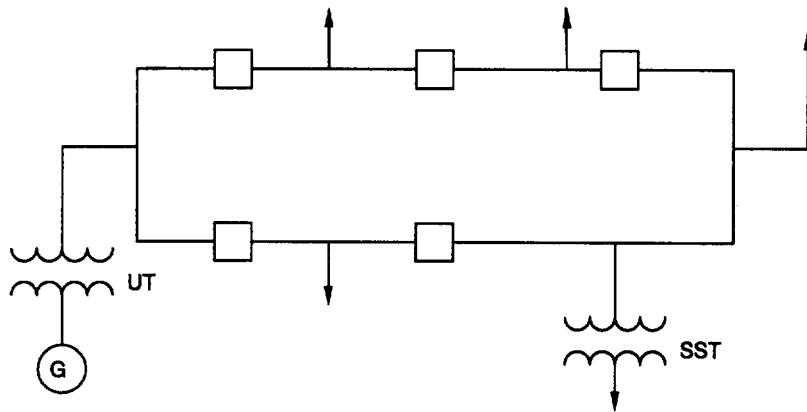
Figure 3.6—Main and transfer bus

c) Figure 3.7 shows two ring bus connections. The ring with separate SST bay position is secure against line faults, unless breaker failure occurs. The ring without separate SST bay position is exposed to faults of the line to which it is connected; however, it saves the cost and area required for an additional

breaker. Both connections are exposed to the possibility that the bus might split if a fault should occur while a breaker is out for maintenance. This may isolate the SST, and the resulting phase angle across the split system may prevent reclosing. [This could also be a factor in transferring station service buses between the SST and UAT. Note that the UT and SST are connected to the ring without sharing a common breaker. This avoids the possible loss of both power feeds as the result of a single failed breaker.](#)



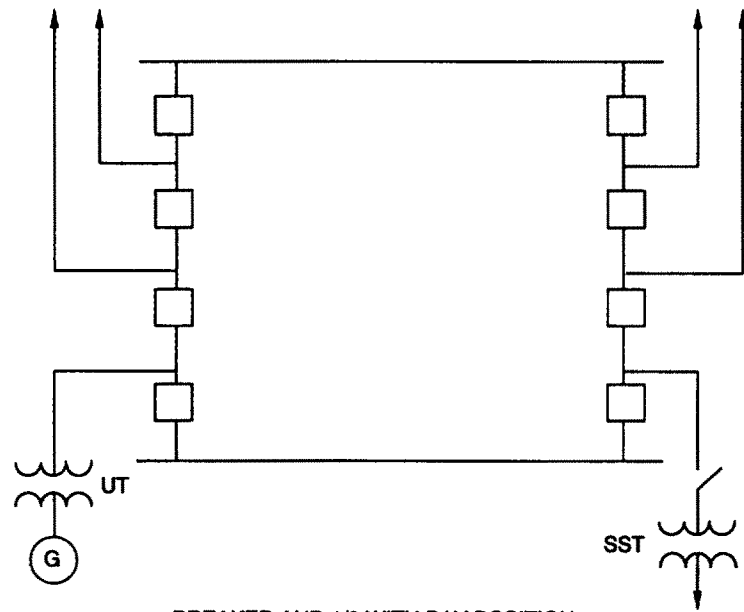
RING BUS, WITH BAY POSITION



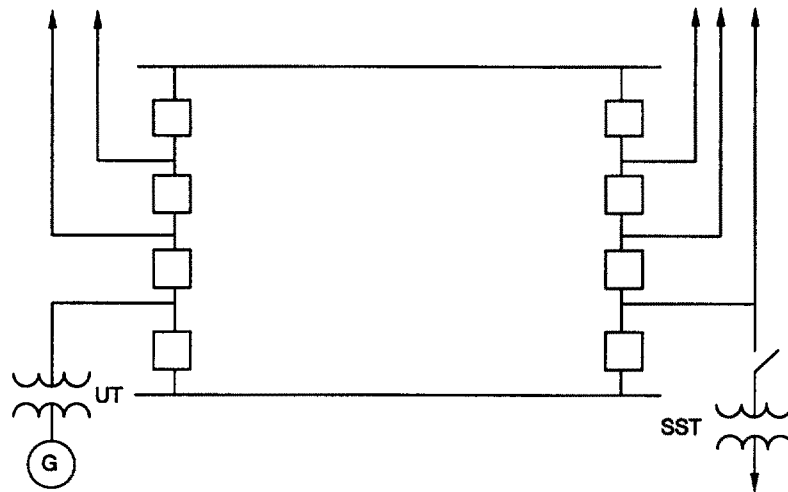
RING BUS, WITHOUT BAY POSITION

Figure 3.7—Ring buses

- d) Figure 3.8 shows a breaker and 1/3 bus. This bus arrangement offers more security than the ring bus because, for certain faults, breaker failure will not cause the SST to be tripped. Two possible SST connections are shown: one without a bay position and one with a bay position. The economies of connecting the SST with a transmission line should be evaluated against the exposure to transmission line interruptions. [Note that the UT and SST are connected to the system without sharing a common breaker. This avoids the possible loss of both power feeds as the result of a single failed breaker.](#)



BREAKER AND 1/3 WITH BAY POSITION



BREAKER AND 1/3 WITHOUT BAY POSITION

Figure 3.8—Breaker and 1/3 buses

- e) Figure 3.9 shows a breaker and 1/2 bus. This arrangement provides a degree of reliability similar to the breaker and 1/3 bus. Again, without bay position and with bay position [for the SST](#) are options to be evaluated. [Note that the UT and SST are connected to the system without sharing a common breaker. This avoids the possible loss of both power feeds as the result of a single failed breaker.](#)

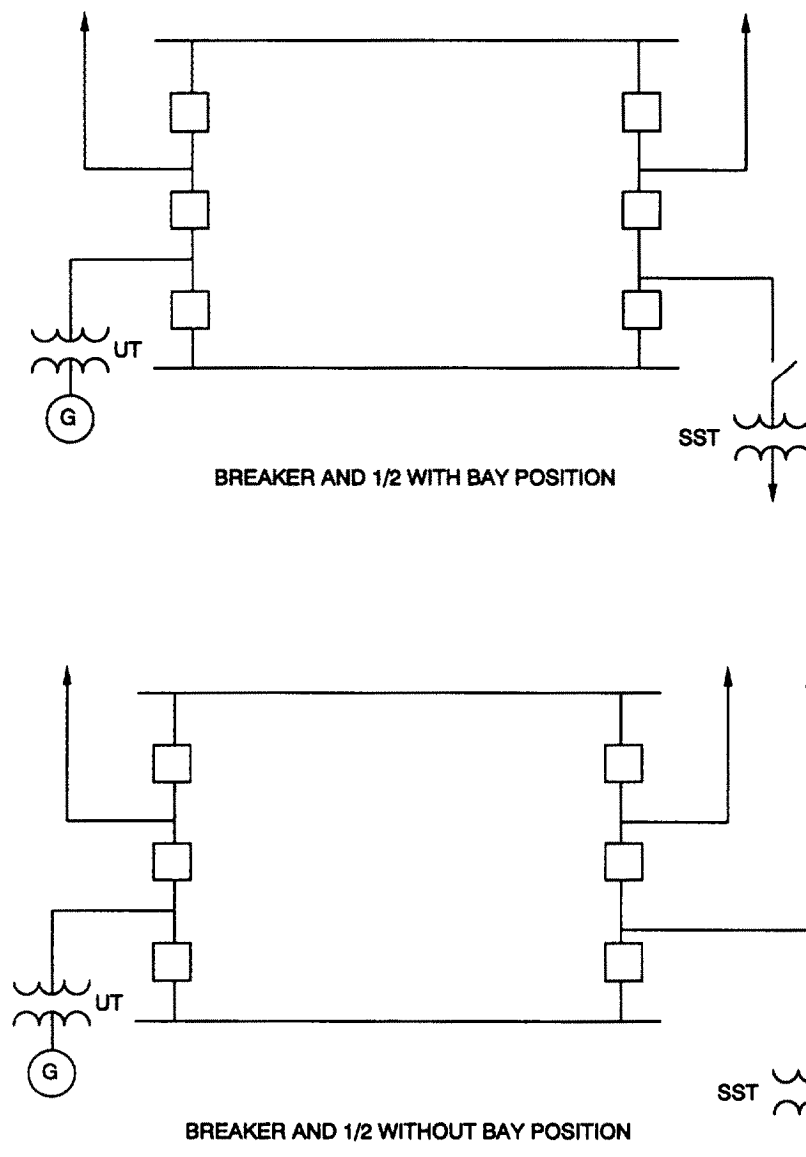


Figure 3.9—Breaker and 1/2 buses

- f) Figure 3.10 illustrates step-down techniques that can be used to connect the utility [high-voltage](#) power system to the station auxiliary buses. The single step is a common arrangement where voltage ratios are acceptable. [Figure 3.10 also illustrates the connection of the SST to an intermediate voltage bus. This is required in some cases where the voltage transformation ratio between the available high-voltage transmission bus and the station service bus is very high. This is fairly common with 345 kV, 500 kV, and higher voltage connections.](#)

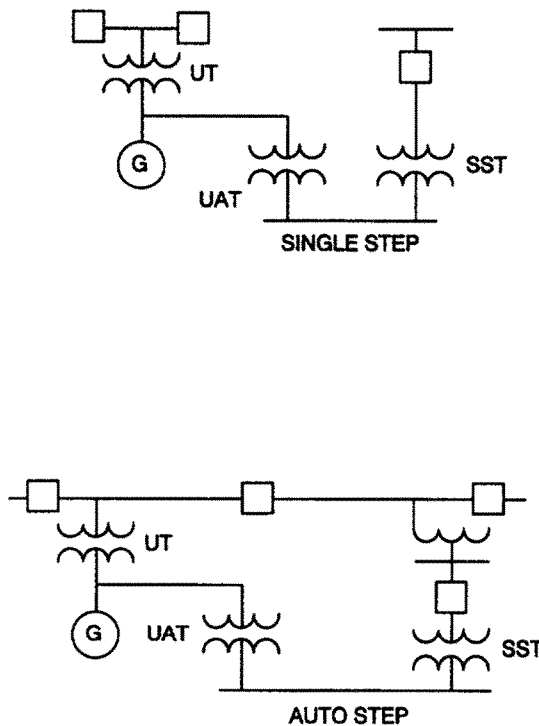


Figure 3.10—Step-down techniques

3.3.2.4.4 Unit auxiliary transformer (UAT) connections

Figure 3.11 through Figure 3.18 illustrate several possible arrangements for the UAT. Since most generating-unit power systems are custom designed, these examples should not be considered all inclusive and are provided to demonstrate basic concepts. Each example arrangement is discussed in more detail below.

- a) Figure 3.11 shows three-winding auxiliary transformers with dual auxiliary voltages and common auxiliary bus. The windings of the UAT and SST may be of the same or different MVA ratings and impedance. Where multiple UATs are used, the MVA and impedance of each UAT are usually the same. The SST may be sized for startup load only or to provide an alternate power supply in the event that a UAT is out of service. The common bus that is served from the SST can be used to serve loads that are common to more than one unit in a multiple unit plant. The SST can also be used for another unit, as indicated by the dotted line to Unit 2. This arrangement may afford some economic advantages as well as space savings although the units lose some flexibility in that only one unit can be started at a time or only one failed UAT can be spared. When the SST is shared, there is also a concern that, should there ever be a multi-unit trip, the total station service load of multiple units would exceed the SST's capability. Another variation is to have two double-winding secondary SSTs sized so that the loss of one SST does not preclude the startup of the generating unit.

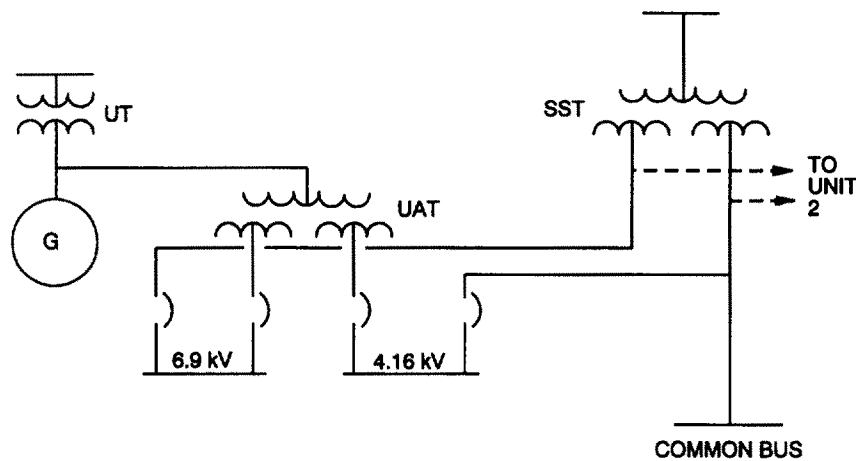


Figure 3.11—Three-winding auxiliary transformers with dual auxiliary and common service bus

- b) Figure 3.12 shows three-winding auxiliary transformers with split auxiliary buses. This arrangement is similar to that of Figure 3.11, except that each secondary winding is connected to serve two auxiliary buses rather than one. This scheme has the advantages of lower continuous current per bus and additional isolation for faults. The disadvantage is that the arrangement will require additional room for the bus locations and extra breakers. These additional costs may be offset partially by using lower continuous-current rating for certain equipment.

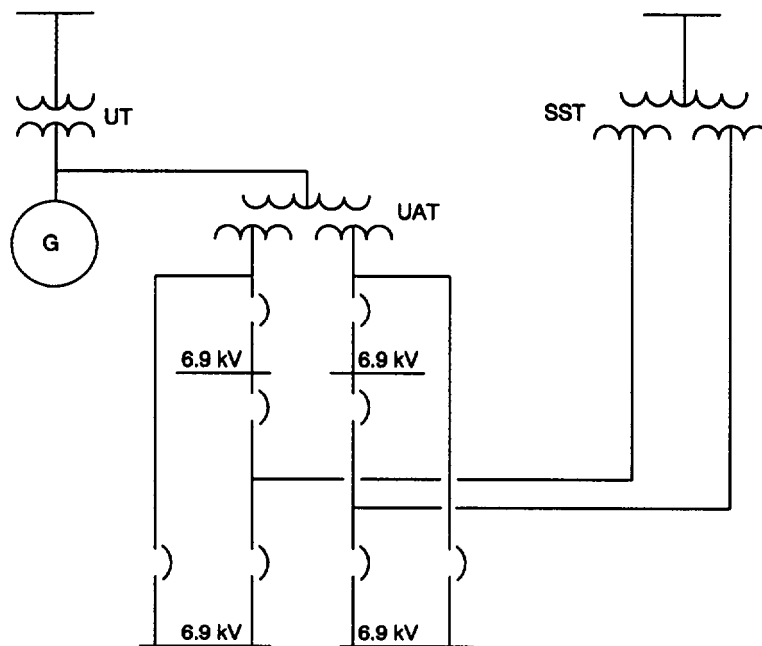


Figure 3.12—Three-winding auxiliary transformers with split auxiliary bus

- c) Figure 3.13 shows two-winding auxiliary transformers with split auxiliary buses. The scheme is similar to Figure 3.12 except for the two-winding transformers. One of the obvious disadvantages of this scheme is the increased cost to serve the same amount of auxiliary load. However, this scheme may improve the overall power system availability to the one shown in Figure 3.12 due to the two-winding transformers.

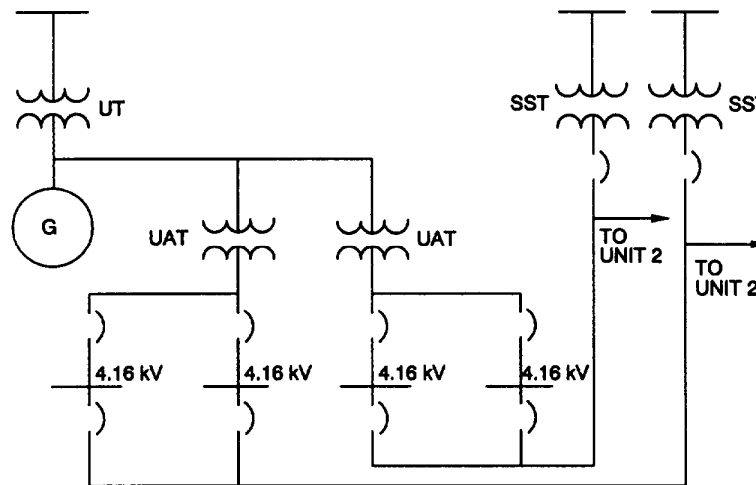


Figure 3.13—Two-winding auxiliary transformers with split auxiliary bus

- d) Figure 3.14 shows dual three-winding auxiliary transformers with dual auxiliary voltage. This arrangement might be used for large auxiliary systems. The MVA ratings, impedance, and voltage are different for each winding of the transformers. Use of different voltages allows segregation of the larger motors to the higher voltage bus for improved regulation and equipment MVA fault capability while providing a more economical voltage for smaller motors. The three-winding transformers save space, which may be critical.

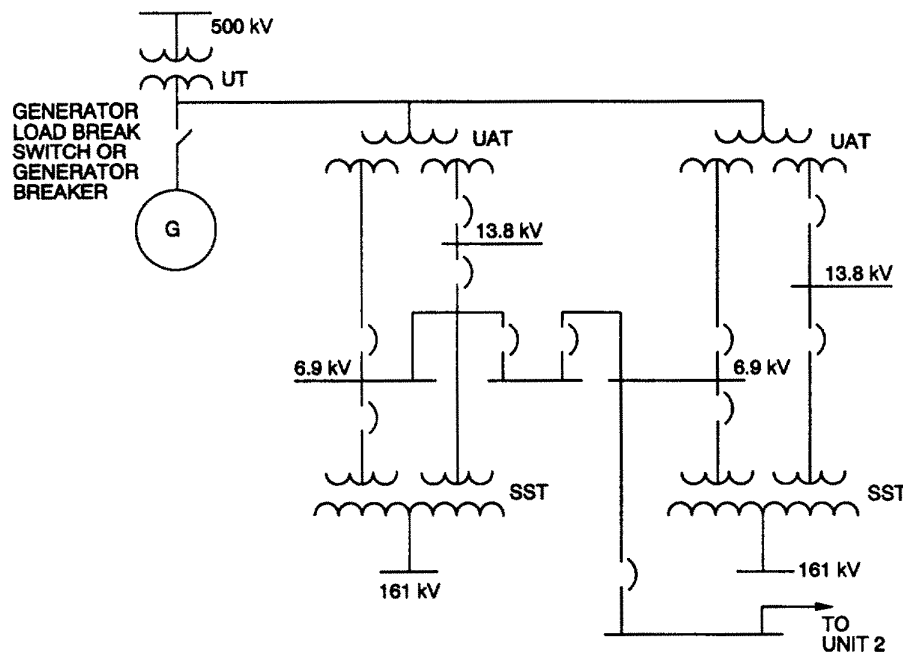


Figure 3.14—Dual three-winding auxiliary transformers with dual auxiliary voltage

- e) Figure 3.15 shows a two-winding auxiliary transformer with dual auxiliary voltage, intermediate auxiliary transformer, and common auxiliary bus. This scheme is unusual but might be used for a large system serving multiple units. The auxiliary transformers supply voltage to an auxiliary (medium voltage) substation. The 13.8 kV buses serve large motors. Smaller motors are supplied from the 4.16

economic advantages and overall system reliability depend on each application. In this design, the starting of 4 kV motors should be closely evaluated due to the additional system impedance caused by the second transformation.

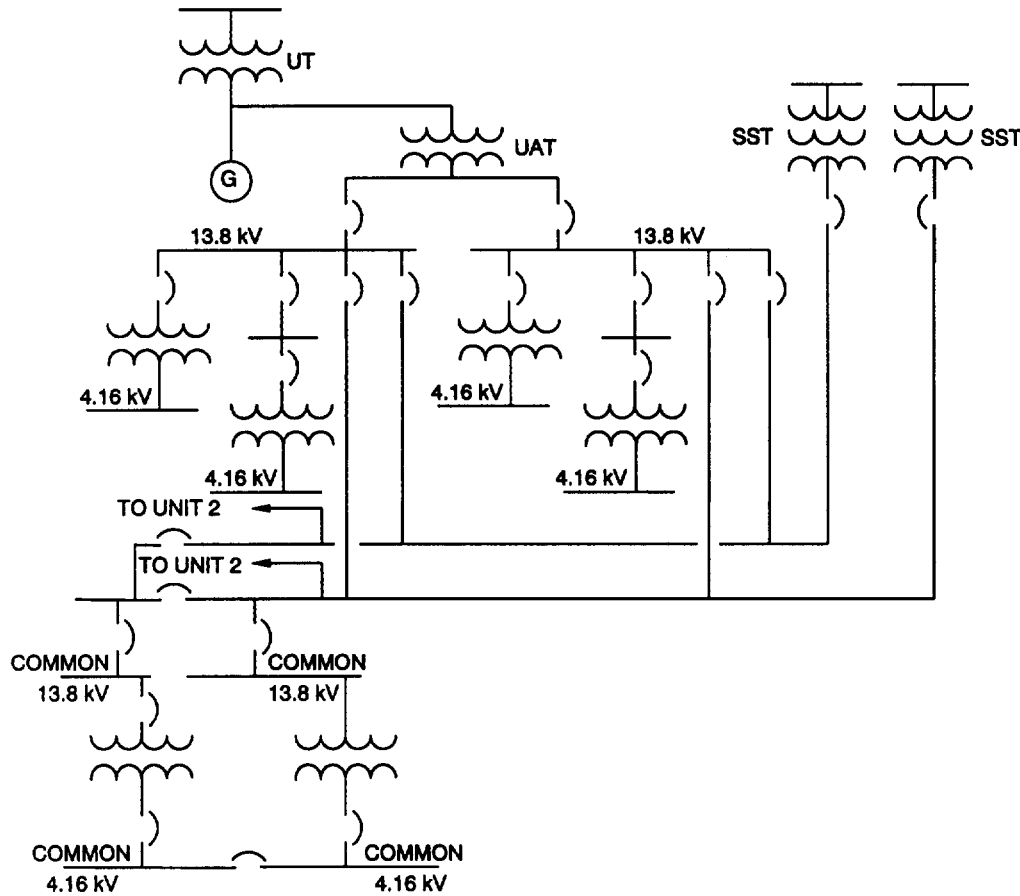


Figure 3.15—Two-winding auxiliary transformer with dual auxiliary voltages, intermediate auxiliary transformers, and common auxiliary bus

- f) Figure 3.16 shows a three-winding UAT—delta tertiary SST with split auxiliary buses and dual auxiliary voltages. This scheme is similar to the other three-winding auxiliary transformers split auxiliary bus arrangements because it has one 13.8 kV winding serving two buses and one 4.16 kV winding serving two buses. The SST arrangement is significant in that the 13.8 kV SST supply is served from the delta tertiary of a system autotransformer. By serving the 13.8 kV direct from the tertiary, one transformation is eliminated, and only a step-down to 4.16 kV from 13.8 kV is required. Using the system autotransformer in this fashion exposes it to more faults and exposes the unit power system to system operations considerations. This could degrade the reliability of both power systems. While this connection represents cost savings in some cases for an integrated utility, there may be economic factors to consider in a deregulated environment. In some cases, this is viewed as a low-voltage (13.8 kV in the example figure) supply. The transmission provider may well have higher capacity and energy charges for station service delivered at 13.8 kV compared to a higher transmission voltage supply to an SST.

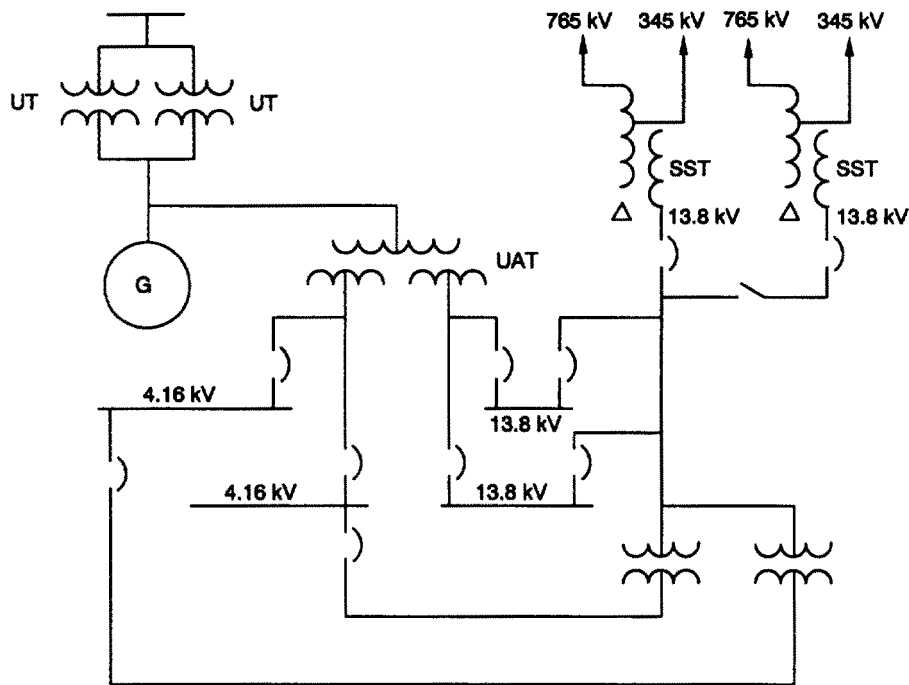


Figure 3.16—Three-winding UAT—delta tertiary SST with split auxiliary buses and dual auxiliary voltage

- g) Figure 3.17 shows a three-winding UAT with generator load-break switch or generator breaker. The significant feature of this arrangement is that a generator load-break switch or generator breaker is used for synchronizing the generator to the transmission system, and for disconnecting it from the transmission system. This allows the SST to be eliminated as the switch or breaker is opened during unit startup with the auxiliary loads served through the UT and UAT. By eliminating the SST, there is no need to transfer the auxiliary loads from the SST to the UAT after unit synchronization. The load-break switch or generator breaker can be used with any number of combinations of UAT arrangements, as the effect is to eliminate the need for the SST for starting the unit. However, if the SST is eliminated, ties to a neighboring unit are required for an alternate source. This could require larger switchgear or [an additional UAT. If a load-break switch is used, then generator faults may result in the tripping of the high-voltage breaker, resulting in temporary loss or transfer of station service until the load-break switch can be opened and the high-side breaker closed.](#)

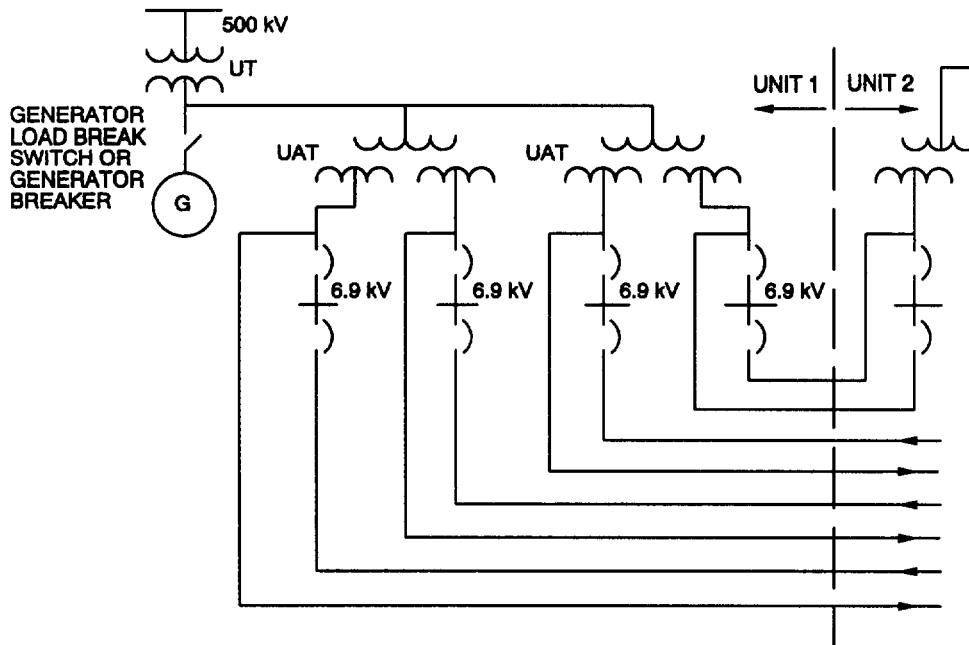


Figure 3.17—Three-winding UAT with generator load-break switch or generator breaker

- h) Figure 3.18 shows the supply from station service only. In this scheme, the UAT is eliminated, and the auxiliary loads are served completely through the SST. In this example, a number of SSTs are used, and, similar to the scheme with a generator breaker or load-break switch, there are a number of possible SST arrangements. The significant point is that the UAT is eliminated as well as the need to transfer auxiliary loads from a UAT to a SST and vice versa. In considering the economics of this scheme, the cost of additional losses and space for the transformer should be evaluated. Note particularly that the UT must carry total generator output rather than generator output minus the auxiliary loads. Thus, the additional load losses through the UT and the additional UT capacity should be evaluated versus SST capital costs and losses. Note also that this example shows multiple UTs that have been applied for increased reliability. This connection does have the advantage that station service buses do not see voltage swings associated with the generator terminal voltage. The generators are normally operated to maintain fairly constant transmission scheduled voltages. In order to accomplish this task, the generator terminal voltage is varied within its allowable range; and if station service is supplied via a UAT, then the generator voltage variation is directly reflected into the station service system. Feeding the station service system from the switchyard SST may reduce some of the complexity in determining the optimum transformer taps to use in the station service system. If widely varying system voltage conditions occur, then transformers with load tap changers may need to be considered.



3.3.2.5 Reliability and availability considerations

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3.3.3 Evaluating alternatives

If more than one plan is given consideration, a method of evaluation must be developed. In addition to costs, there are several other factors that may influence the selection of a particular plan. Some of the more important factors are discussed in 3.3.3.1 through 3.3.3.8.

3.3.3.1 Preliminary cost analysis

After the alternative plans have been developed, the quantity of schemes that appear attractive may be cumbersome. It is helpful to reduce the number of alternatives to a manageable size, or perhaps to one plan, for detailed design consideration. Evaluating preliminary cost data for each scheme is an effective tool in this reduction process.

3.3.3.2 Reliability

Mathematical techniques for analyzing reliability indices can be used to determine relative reliability levels. The analysis should include a review of system performance for single failure and multiple failure criteria. Not only should the probability of such failures be studied, but also the effect on the auxiliary system should be determined. The frequency of failure, modes of failure, outage times, and repair times should all be evaluated. Systems may then be designed to withstand single, double, or multiple failures and continue to function. As evaluation techniques and the necessary reliability databases improve, mathematical reliability analysis should become a standard part of the investigation. If a mathematical analysis is not used to evaluate reliability, some subjective evaluation should be used. The critical items in the systems should be identified, and their relative reliabilities should be noted. In this way, perhaps some weight can be placed on the different reliabilities, which should help in selecting a preferred scheme.

3.3.3.3 Flexibility

The auxiliary system design requires a high degree of flexibility to accommodate design changes that will be made later. Thus, margins on equipment ratings, space for additional equipment, and capacity to account for increased load should be given serious study.

3.3.3.4 Maintenance

While maintenance is largely the responsibility of plant personnel, the auxiliary system designer can take certain steps to improve system reliability. For example, the scheme might permit some of the maintenance to be performed with the unit carrying load. This could be accomplished by providing spare capacity for certain loads or alternate feeds to the loads. If the designer specifies the equipment to be purchased for the auxiliary system, then the expected maintenance of the competitive systems should be evaluated. This information may also influence the on-site spare parts purchasing policy for the plant.

Another issue to be considered in the plant design is the ability to maintain continuity of service to buses that are used during normal operation and maintenance outages such as lighting, cranes, welding receptacles, etc. One solution is to power these loads from a dedicated outage motor control center (MCC), which can be switched between two supplies, providing an opportunity to maintain the supply buses.

3.3.3.5 Expandability

Most auxiliary systems experience some expansion or load growth after the initial design. Some causes for increased loads are as follows:

- a) Larger mechanical loads than anticipated
- b) Coal- and ash-handling facility modifications associated with fuel supply economics (fuel switches) or environmental reasons

- c) Efficiency and availability improvements (i.e., balanced draft conversions)
- d) Unit cycling requirements, such as electric drives for existing turbine-driven load (i.e., boiler feed pump)
- e) Environmental, such as precipitators, flue gas desulfurization, [selective catalytic conversion](#)
- f) [Increased output rating of units resulting in station service load increases](#)

In any case, expansion is almost inevitable, and the designer is well advised to make allowance for future changes. The exact amount of margin to be provided is a matter of engineering judgment for the designer, as it may vary among companies. For example, some companies provide for a future load growth of $X\%$, where the determination of an amount (X) of future load growth capability depends on several factors including costs and the probability of the modification.

3.3.3.6 Performing detail design calculations

Design calculations allow a complete technical evaluation of the plans under study to determine the merits of each compared to the design criteria. These calculations should include short-circuit and continuous current, steady-state voltage profiles and transient voltage dips during motor starting, etc. Once the final plan is chosen, these detail calculations provide equipment characteristics [for equipment specifications](#) such as transformer MVA rating and impedance, breaker ratings, etc. [The designer should specify plans for the operation of motor loads into the motor service factor rating \(see 11.4.2.4\).](#) This is an integral input into the equipment specifications.

3.3.3.7 Detailed cost analysis

There are several components of costs that should be evaluated, as well as several methods of economic evaluation that are appropriate. The details of these evaluation techniques are beyond the scope of this document. There are, however, many excellent texts on the subject.

The costs to be evaluated include, for example, capital, maintenance, and operating costs. Note that maintenance costs and operating costs are distinct. The maintenance costs refer to the costs associated with items such as annual maintenance, repairs, and replacement parts for the system equipment. The operating costs refer to the costs associated with items such as losses or replacement power. [The operating costs may also include a cost comparison for purchasing station service power at various transmission voltage levels. This can be a significant factor when station service power is taken from a point in the transmission grid other than the location where the generator's output is injected into the transmission grid.](#) These separate cost components may individually influence the overall economic evaluation of the plans.

3.3.3.8 Choosing a scheme

After evaluating all plans for reliability, flexibility, maintenance, expandability, and cost, a final scheme is chosen.

3.3.4 Preparing equipment specifications

The equipment specifications can be written based on the detailed design calculations of the chosen scheme. The specifications should assure that all requirements determined in the detail design calculations, and any special requirements, such as operating duty cycles, are met by the manufacturer. The form of such specifications is beyond the scope of this text, although many IEEE documents provide guidance in preparing the specifications.

3.3.5 Evaluating the bids

The details of the bid evaluation process are also beyond the scope of this text, but it is the next step in the design process. The methods of evaluation may vary widely, but the results should reflect evaluation techniques similar to those used in 3.3.3.

3.3.6 Reviewing and finalizing design

Once the equipment for the auxiliary system has been specified and purchased, the manufacturers can supply the designer with design documents for the equipment. At this point, the design should be reviewed, using the design data for the equipment, to determine if there are any equipment changes that may impact the auxiliary system design. For example, a large motor may have an inrush current that exceeds specifications. This may result in unacceptable voltage drop during starting. Major changes are generally infrequent, but the designer should check the design data for possible changes.

3.4 Transmission system and generating unit considerations

The power system discussed in this subclause encompasses the power transmission system and the generating unit.

3.4.1 Transmission system

3.4.1.1 Voltage variations

The maximum and minimum expected voltages to the primaries of the station service transformers are necessary data in determining the voltage regulation requirements of these transformers. These expected voltages are obtained from the transmission planning engineer who analyzes the transmission system by running a series of power flow simulations. For a more accurate representation, these power flows should be run including the station service load. If the station service load is neglected, then regulation should be calculated through the transmission system (see 3.4.1.2). The minimum system voltage, maximum system impedance, and maximum station service load determine the minimum voltage. The maximum system voltage, minimum system impedance, and minimum station service load determine the maximum voltage.

This analysis is important in determining the station service transformer impedances and tap requirements. Large voltage variations may necessitate the use of load tap changers or transformer thermal load limits that are lower than their top ratings. Also, transformer overexcitation limits should be considered, especially when applying taps below nominal voltage.

3.4.1.2 Representation of transmission system as short-circuit impedance

For station service voltage regulation purposes, it is usually adequate to represent the power system as a voltage source behind a short-circuit impedance. The maximum and minimum power system short-circuit impedances can be obtained by investigating combinations of line and unit outages. This is usually done with a digital short-circuit program. For maximum short-circuit contribution from the transmission system, the maximum transmission system voltage and minimum transmission system impedance are used. The station service transformer is typically the only component that can be changed to limit the fault contribution from the transmission system. Therefore, for a given station service load, transformer tap setting, system voltage, system short-circuit impedance, and auxiliary bus short-circuit rating, the required transformer impedance(s) can be determined. Of course, this impedance should also satisfy voltage regulation requirements as noted in 3.4.1.1. As a first evaluation criteria, a near-zero transmission system impedance (infinite bus) might be used. If acceptable, an infinite bus assumption should be used because fault current exposure of the auxiliary system equipment will be reduced as transmission system growth occurs over time.

3.4.1.3 Phase-sequence and phase-angle difference

For three-phase power systems, phase sequence identifies the order in which the three voltages reach their positive maximum values relative to a fixed reference point. When interconnecting individual equipment and/or power systems, the phase sequence of the two must be equivalent. Proper care is required when dealing with phase-sequence-sensitive equipment such as motors, generators (proper rotation), transformers (proper phase shift), certain types of protective relays, etc. Thus, when designing a new or modifying an existing power system for a generating station, the phase sequence of the system and equipment must be considered in conjunction with the phase-angle difference described below.

A difference in phase angle between the unit and the station power supplies can result in severe duty on equipment such as transformers, motors, and breakers during the transfer [of station load buses](#) from the station service transformer to the unit auxiliary transformer and vice versa. Phase-angle differences are both steady state and transient in nature. Transient phase-angle differences in the auxiliary power supply can be caused by disturbances on the utility power system or, more frequently, by an automatic transfer from the unit transformer to the startup transformer. Auxiliary bus transfer is discussed in 4.6. The steady-state phase-angle difference between the unit auxiliary transformer and the station service transformer is caused either by the transmitting of power through the power system or by three-phase transformer winding connections.

The generating unit and station service transformer(s) may be connected to the transmission system at two different electrical points although they are at the same physical location. An example of this might be a unit transformer connected to 500 kV and the station service transformer connected to 115 kV. These two transformers may be connected at the generating unit by an autotransformer or step-down transformer, or they may be connected only by virtue of the interconnected transmission system. The maximum angle difference between the generating unit and the station service transformer(s) for the worst power flow is determined by the transmission planning engineer by running power flow cases. The power system should be designed and the equipment purchased to be capable of tolerating the maximum angle determined because this angle cannot be judiciously adjusted to zero.

The phase-angle difference due to transformer winding connections (i.e., wye-delta, delta-zig-zag, etc.) must also be examined. In cases where two systems are to be paralleled, such as during parallel transfer (see 4.6), the phase-angle difference between the two sources should be [near](#) zero. Even in the case of radial systems, it is good practice to maintain a zero phase difference at each voltage level, where practical, in the event these systems are inadvertently interconnected or some form of automatic throw-over scheme is added. Note that this may require the use of transformers with nonstandard phase connections. An example of correct and incorrect connections is given in Figure 3.19.

3.4.2 Generator

[The main power generator is beyond the scope of this guide; however, its operating range must be factored into the auxiliary system design.](#)

- a) *MVA rating.* The MVA rating of the generating unit has a direct influence on the design of auxiliary systems. In general, the larger the main generator, the larger the power consumed by the auxiliary system. In the past, coal-fired unit auxiliary power systems consumed 5% to 8% of generator output. However, with the rapid increase in stringent environmental laws, the power consumed by auxiliary power systems has risen in some coal-fired units to 10% to 12% of the generator rating. The increase in the auxiliary system capacity has also resulted in the design of the auxiliary system becoming more complex. [In simple or combined cycle combustion turbine-based plants, the station service load is usually 1.5% to 5.0% of the generator rating.](#)

As the MVA rating of the unit increases, the desired reliability of the unit increases accordingly. This is because the larger units are intended for base load operations and because the initial cost of the unit and energy replacement costs are very high.

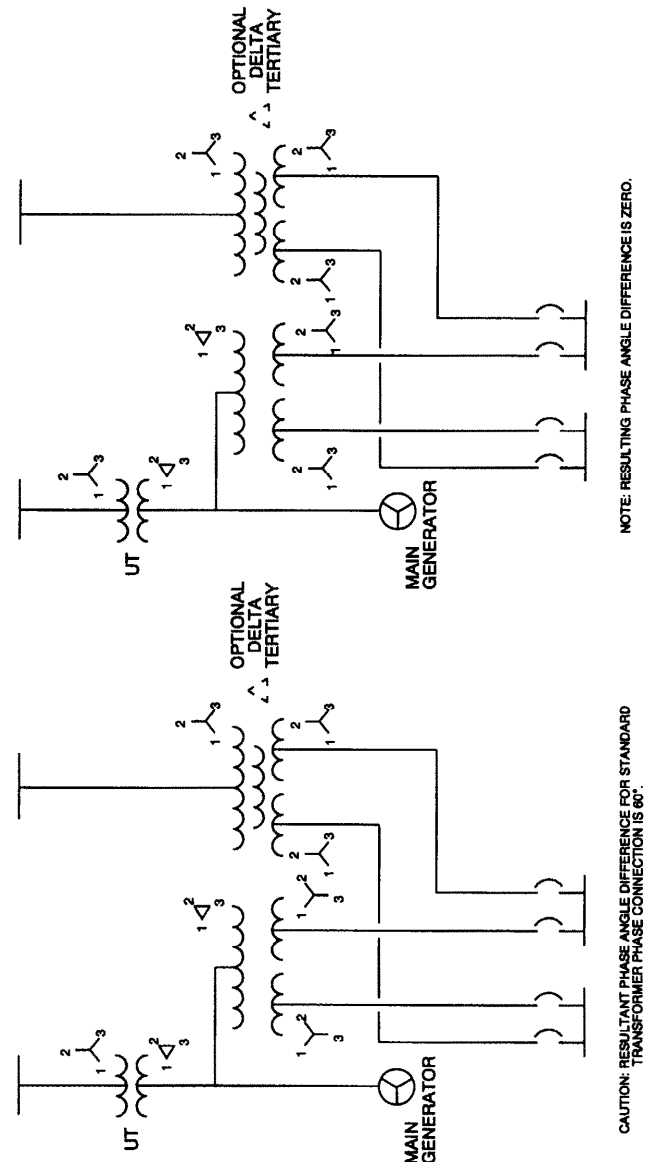


Figure 3.19—Phase shift due to three-phase transformer winding connections

- b) *Voltage rating.* As stated in IEEE Std C50.13™-2005 [B5], “Generators shall be thermally capable of continuous operation within the confines of their reactive capability curves over the ranges of $\pm 5\%$ in voltage ~~not more than five percent above or below rated voltage~~..., but not necessarily in accordance with the standards of performance established for operation at rated voltage....” This implies that the auxiliary power supply system connected to the main generator bus should allow a $\pm 5\%$ generator bus voltage swing.

For cases where this is true, it may necessitate increasing the number of auxiliary buses or the use of transformers with load tap changers. An alternative to this is to determine the required generator bus voltage swing. This requires a study of unit transformer regulation, tap settings, power system reactive power requirements, transmission system voltage schedules, and the coordination of these with the unit auxiliary loads, station service, and load-center transformer tap settings. The results of this type of study may indicate that the station auxiliary system equipment voltage requirements limit the allowable voltage swing of the generator. This could impact the ability of a generator to supply reactive power, in vars, to the transmission system

3.4.3 Unit connections

A primary decision to be made for the unit connection is whether or not to use a generator breaker or load-break switch (see Figure 3.14). This decision may not rest solely on the auxiliary power supply system requirements. However, it does have a major impact on the auxiliary power system design. The most significant impact of applying a generator breaker or a generator load-break switch is the possible elimination of the station service transformer. In the event that the station-service transformer is retained, it could serve as a third source of power to the auxiliary system. In the absence of the station service transformer, the auxiliary system under unit startup or similar conditions is fed through the unit transformer, and the alternate source is from neighboring units. Consequently, the power from the transmission system to the auxiliary system flows through two transformers: the unit transformer and the unit auxiliary transformer. Thus, voltage regulation and the short-circuit contribution from the system will be dependent on the relative strengths of the transmission system and the tap setting of the unit transformer. The tap of the unit transformer is normally set for the operation of the transmission system and not to supply the auxiliary loads. One other consideration is making sure that the generator bus has a ground reference when the generator breaker is open. This can be accomplished with a set of instrument voltage transformers on the bus that are carrying enough load to provide the reference signal.

3.4.4 Station service transformer connections

The station service transformer connection requirements are influenced by the factors discussed in 3.4.4.1 and 3.4.4.2.

3.4.4.1 Transmission system nominal voltage

The transmission system supply voltage is usually greater than or equal to 115 kV. The transformations necessary are dependent on this nominal voltage and the availability of transformers to step this voltage down to the auxiliary power system voltages. For example, for a transmission system of 500 kV, it may be more economical to step-down the voltage to an intermediate level, such as 115 kV or 230 kV, and then step-down the voltages to 6.9 kV, 4.16 kV, or 2.4 kV. Another option is to use the tertiary of an existing autotransformer as the source of the desired voltage (see Figure 3.16).

3.4.4.2 Transformer type

The extent to which the type of transformer (i.e., two or three winding) affects the design is dependent upon the design and operating philosophies of individual utility companies. For example, some utilities prefer to have balanced winding loadings on three-winding transformers. Under such conditions, the secondary voltage is limited to one choice. Dual auxiliary voltage systems would require two-winding transformers for this restriction. Other utilities have successfully utilized three-winding transformers with secondaries at unequal loads and voltages.

Another design factor is the manufacturers' impedance tolerance. The standard tolerance is $\pm 10\%$ and $\pm 7.5\%$ for three- and two-winding transformers respectively (see [ANSI IEEE Std C57.12.00™ \[B6\]](#)). The difference in tolerance can have a significant effect on the preliminary design phase of the auxiliary power systems.

In the preliminary design, the exact impedance of the auxiliary transformer is initially unknown. In order to calculate the transformer impedance, the manufacturer's impedance tolerance is appropriately taken into account for short-circuit and voltage regulation calculations. A difference of 2.5% in impedance tolerance may be critical under certain design conditions and may warrant a change. For example, the change may materialize in the preference of one type of transformer to another, the reduction in auxiliary bus load, or the change in design boundary constraints.

3.4.5 Transformer duty

The unit auxiliary transformer and station service transformer are subject to experiencing special duties. Depending on the design of the power system, these transformers may be exposed to synchronizing surges, large inrush currents due to transfer of the auxiliary loads and starting of larger motors, etc. Since a unit auxiliary transformer is connected to the generator bus, it can be exposed to severe through-fault conditions that cannot be isolated from the generator if a generator breaker is not used or fails to operate. It should therefore be designed to handle the fault decrement of the generator resulting from the trapped flux in the machine. In addition, the unit auxiliary transformer has the exposure to overvolts per hertz events caused by improper generator voltage and/or speed or sudden loss of load (full-load rejection).

These special duties should be quantified and made part of the transformer specification. They are addressed in more detail in Clause 9.

3.5 Bibliography

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[B3] Cavallaro, S., “Application of Generator Circuit Breakers to Nuclear Power Stations,” IEEE PES Winter Power Meeting 1975, New York, NY, C75 191-2.

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[B5] IEEE Std C50.13TM, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above.⁴

[B6] IEEE Std C57.12.00TM, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

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²ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ

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⁴The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

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[B13] Scherer, H. N., Jr., Olhen, M. I., and Ettlinger, L. E., “AEP 1300 MW Units: Engineering and Design Features,” IEEE PES Winter Meeting 1975, New York, NY, T75 178–9.

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4. Startup and shutdown requirements

4.1 General

Auxiliary loads for a power station generating unit and its prime mover (turbine or engine) require electric power service during startup and shutdown periods. This service is normally supplied from off-site sources through the transmission system and, in the case of a large or multi-unit plant, through its own switchyard. This supply, with its related equipment, is identified as either the station service system or the startup/shutdown source. [Another method is backfeeding through the unit transformer and the unit auxiliary transformer when a generator breaker or load break switch is used as shown in Figure 4.1 \(in 4.4.1\).](#) After a unit generator has been synchronized to the system and partially loaded and transfer [from the station service transformer to the unit auxiliary transformer](#) has taken place, service to its auxiliary loads is supplied normally from the unit generator terminals through a unit auxiliary transformer. This supply is identified as either the unit auxiliary system or the normal source.

Station service systems should be suitable for supplying continuous load, short-time overload, and transient overload requirements of the unit auxiliary loads. They also should provide margin for future load growth. Quality of power is an important consideration that should meet criteria for frequency, phasing, and voltage control.

Power from the station service system is essential during unit startup and shutdown periods in which the unit generator cannot supply its auxiliary loads. The station service system typically provides power to loads for lubrication and sealing oil during and after coastdown, removes residual heat, purges the boiler, maintains condenser vacuum, and provides service to other critical components and protective systems. [For combustion turbine plants, the station service system provides power to the starting system, which is typically either a static start device or a starting motor.](#)

Onsite power sources, either storage batteries or engine-driven generators, are used to provide standby or alternate electric service to critical equipment in the event that both the normal and startup/shutdown sources fail during operation. When this occurs and the power system is completely shut down or blacked-out, the design bases of the plant may require that the unit be restarted (called a *black start*) from a power source that can be manually initiated. Generators driven by hydraulic turbines, gas turbines, or diesel engines are used for this and other emergency shutdown tasks until the startup source is restored. Due consideration should be given to size and cost. If these sources require stored electrical energy for startup, such as field flashing, controls for diesel generators, or ignition, it is usually obtained from storage batteries.

4.2 Power requirements

Power requirements for unit auxiliary loads at startup (or shutdown) are dependent on the size and type of unit and the degree of reliability. The design should include considerations for continuous load, short-time and transient overload, and a margin for future growth.

4.2.1 Continuous capability

The continuous capability should supply maximum power requirements of all electrical auxiliary loads in any combination in which they may be used during plant operation from the station service system. Where more than one unit is supplied from a common station service system, consideration should be given to the possibility that a unit in normal operation may trip from full load and transfer its shutdown auxiliary loads to the common station service system during the startup of another unit's auxiliary loads. Instead of designing a system to supply auxiliary loads requirements for two units, it may be acceptable to impose engineering or administrative load limitations. The system should also be able to react in the event that station load is suddenly lost.

4.2.2 Short-time overload capability

Certain auxiliary loads served by station service systems may be required, for limited periods, to carry loads greater than those existing at plant full load. Examples are circulating water pumps filling the system before full syphon conditions are established, induced-draft fans handling cold air, motor-driven startup boiler feed pumps that will be replaced by turbine-driven pumps at a more advanced stage of startup, electric boilers not used during full-load operation, [and the starting systems for combustion turbines](#). Affected equipment or components of the service system should be capable of carrying these overloads for appropriate periods without producing voltage profiles or temperature rises outside prudent limits. While reviewing equipment load requirements that are greater during starting than at full-load operating conditions, equipment whose load requirements are lower during starting should also be noted. A typical example would be the forced-draft fans of a unit, which operate substantially below nameplate rating during startup. Incorporating both types of load in a common portion of the system may reduce the overall supply requirements.

4.2.3 Transient overload capability

Station service systems should have the capability of supplying electrical auxiliary loads during the starting or restarting of the largest load. When the largest load is a motor driving high-inertia loads, such as an induced-draft fan, the starting transient duration may be up to 60 s. Voltage profiles during such transients are not required to satisfy criteria established for continuous operation or short-time overload, but they should be adequate to assure that no running motor will stall and no motor-starter contactor will drop out. Acceptable equipment operating voltage ranges should be confirmed with the manufacturer. If load-tap-changing (LTC) transformers are used in the power system, it should be assumed that these tap changers do not operate fast enough to apply significant correction during such transients.

The system should be capable of supplying unit auxiliary loads required during an automatic transfer of the buses from the normal to the startup/shutdown source, [where applicable](#). Voltage profiles immediately following such transfers should meet the same criteria as those established for the motor-starting transient. Within approximately 60 s, the profiles should meet criteria established for continuous operation. If transformers with LTC are used, it should be assumed that significant correction is not applied until after the 60 s period.

4.2.4 Margin for load growth

Station service system design should allow for auxiliary loads that may be added after the plant is placed in service. An acceptable margin for future loads should be considered in transformer and feeder cable capacity and space should be provided for switchgear and motor control center additions. Short-circuit withstand capability of switchgear buses should be sufficient to avoid transformer voltage regulation problems and allow for future

growth. This last margin generally will be created by increasing transformer impedance at the expense of voltage regulation. For that reason, it is often impractical to make large allowances for future load growth.

4.3 Quality of power

Quality of power is a term used herein to designate system characteristics such as availability, frequency, phasing, wave form, and voltage control. The design should consider the effect these characteristics have on satisfactory operation of the system and its components. [For the purposes of this guide, availability is considered as a measure of power quality.](#)

4.3.1 Source availability

Availability of station service may affect the availability of a generating unit. Replacement power costs, incurred when an otherwise serviceable generating unit cannot be started, may be a significant item. In addition, a shutdown of the unit without power to run the auxiliary loads may cause equipment damage, the repair of which will delay restart and incur replacement power costs. For these reasons, the cost of an alternate power source may be justified, particularly in a multi-unit station. This alternative power source may be the station service system, an onsite source, or both. The basis of selection should include a review of the reliability of the transmission grid, outage costs, and onsite source equipment costs.

4.3.2 Frequency

When a transmission system is supplying power through the station service system, the frequency at normal operation is maintained at approximately $60 \text{ Hz} \pm 1\%$. Exact tolerances are dependent on utility system operating conditions and procedures. Continuous operation outside of these tolerances may significantly affect output of larger unit auxiliary loads (reduced pressures and flows) and may cause vibration problems in the turbine blading. When the power supply is from an onsite ac source, frequency is usually maintained at 60 Hz with a tolerance within $\pm 3\%$. Exact tolerances are dependent on the specific generator and the type of governor control used; however, operation of equipment beyond its volts per hertz rating can cause equipment damage.

4.3.3 Phasing

When an alternative source is available continuously to accept a transfer of the auxiliary loads bus from the normal source, its frequency and phasing should match that of the normal source. Excessive phase-angle differences may result in significant transfer of power from one source to the other during parallel operation. Phase-angle differences relating to auxiliary loads bus transfers, parallel source operation, and related equipment damage are described in more detail in 4.6.

4.3.4 Phase balance

Phase-to-phase voltages should be balanced within [1% without derating and up to 5% with derating](#). Percent unbalance is defined (see NEMA MG 1 [B15]⁵) as 100 times the maximum voltage deviation from the average voltage divided by the average voltage. The reason for this requirement is that, at normal operating speed, the motor phase current unbalance will be 6 to 10 times the voltage unbalance. This phase current unbalance produces winding currents significantly in excess of those present under balanced voltage conditions. The increased currents will cause a higher-than-normal temperature rise in the motor and may require the derating of the motor nameplate horsepower to prevent long-term damage. Under a condition of 5 % voltage unbalance, the motor derating factor may be as large as 75% of the nameplate horsepower. An additional effect of voltage unbalance is that the locked-rotor and breakdown torques will be decreased, and the motor may no longer be adequate for its intended application. The above applies specifically to induction motors. Situations in which larger unbalanced voltages exist, or in which synchronous motors are supplied by unbalanced voltages, should be stated in the motor specifications.

4.3.5 Waveform

The voltage waveform should be sinusoidal with a deviation factor not exceeding 0.10 (NEMA MG 1 [B15]). Deviation factor is defined as the ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave when the waves are superimposed in such a way as to make this maximum difference as small as possible.

4.3.6 Voltage control

Startup/shutdown source voltages should furnish a range of voltage that ensures acceptable operation of the auxiliary loads. The normal source is usually a transmission or distribution system voltage that will be transformed onsite to a lower utilization voltage. ANSI C84.1 [B3] establishes voltage ratings and recommends that source voltages should have a sustained value of between 98.5% and 105% of the nominal voltage, corresponding to Range B. It should be noted that these values are recommendations only, and the required range is a function of the specific design of the auxiliary service system and the specific operating ranges of the equipment. Most auxiliary equipment will operate within a $\pm 10\%$ tolerance of their nominal voltage rating. The compromise made between increasing transformer impedance to lower short-circuit availabilities and decreasing transformer impedance to raise operating voltages will also affect the required source voltage range. Proper selection of transformer impedances and tap settings, in conjunction with a station design that minimizes voltage drops, should result in selection of a range within the normal operation of the source voltage. When a range of voltage is required that is wider than the capability of the source, it may be necessary to reconsider the single-line design before employing load tap changers in the transformer stepping the voltage down to utilization level. Both system and auxiliary equipment utilization voltages are addressed in greater detail in Clause 5.

⁵ The numbers in brackets correspond to the numbers of the bibliography in 4.10.

Source voltages may have transient values outside the above range. Transient overvoltages caused by lightning or switching should be limited by appropriate surge protection to prevent damage to transformers, switchgear, and utilization equipment on the system. Transient under-voltages produced by faults on the transmission or station service system are of short duration (because of rapid fault clearing) and have little effect on utilization equipment.

Transient undervoltages caused by starting large motors are frequently of sufficient duration to warrant careful study. The magnitude of such transients depends on the ratio of the source impedance to the motor locked-rotor impedance. The source and feeder voltage regulation will be adversely affected by other running loads and by transformer and cable impedances between source and motor.

Transient undervoltages caused by sudden transfers of large blocks of load from the normal to the startup source may be unacceptable if the voltage difference between the new source and the residual bus exceeds 1.33 per unit (p.u.) This may occur if the dead-bus time of the transfer exceeds 4 to 6 cycles. Dead-bus time is the time in which the auxiliary load's service bus is completely without power. Slower transfers may require load shedding to maintain the voltage within acceptable limits. Voltage transient conditions caused by bus transfers are described in more detail in 4.6.

In general, the startup source should have a short-circuit capability greater than 30 times the magnitude of its steady-state load. In this case, the startup source is assumed to be the high side of the station service transformers. Therefore, a total demand of 50 MVA would require that the source have a minimum short-circuit capability of 1500 MVA. If this requirement can be met, the transient undervoltages may be acceptable, and a narrow range of sustained source voltages may permit acceptance of a lower short-circuit capability. However, it should be emphasized that the above statement is a general guideline only. The actual MVA and impedance values of the station service and unit auxiliary loads service systems should always be used for calculating the electrical system performance of the final plant design.