

IEEE Design Guide for Electric Power Service Systems for Generating Stations

Sponsor

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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 contained herein 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

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Foreword

(This foreword is not a part of IEEE Std 666-1991, IEEE Design Guide for Electric Power Service Systems for Generating Stations.)

This document is primarily tutorial in nature as it is intended to provide guidance and direction in the design of electric power service systems for electric power generation plants. The guidance and direction given in this document 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.

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IEEE Design Guide for Electric Power Service Systems for Generating Stations

1. Introduction

This design guide applies to station service systems that supply electric power to auxiliaries 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 is good practice for the many different types of electric power service systems for generating stations. It is anticipated that this guide will assist those who must establish the criteria for the design of generating station auxiliaries 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 auxiliaries 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 auxiliaries 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 auxiliaries 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 section, as appropriate, has a bibliography of 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 Introduction

An electric power generating station can only produce power if its auxiliaries are functioning. Upon loss of supply power to these auxiliaries, a unit may be idled or damaged. The electric power supply system for auxiliaries 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 auxiliaries system.

Power system engineers who plan and design an auxiliaries system must be aware of the need for a well planned, well engineered, and reliable auxiliaries 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 section, 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 auxiliaries system.

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

- 1) Typical power plant auxiliary loads and their power service requirements
- 2) Typical power service parameters including how and why they must be considered
- 3) Typical power service components and their design requirements
- 4) Typical power system design requirements and limitations

3.2 Basic Design Considerations

Many factors are considered in the overall planning and design of an auxiliaries system for a generating station. These factors influence the design and operation of a 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 auxiliaries 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

- 1) 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 or other alternate ac or dc sources, depending upon the criticalness and nature of the load.
- 2) Power supplies and critical loads should be divided between unit auxiliaries buses so that the failure of any one bus or power supply will not prevent the safe shutdown of the unit.
- 3) 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 auxiliaries, the reliability of the auxiliaries system directly effects 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:

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

The reliability of the auxiliaries power supply system should be consistent with the importance of the unit to the power system, industry codes and standards, and regulatory requirements.

3.2.3 Cost

Capital operating and maintenance costs of the auxiliaries 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

Auxiliaries 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 auxiliaries 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 must be considered to determine the true increase in reliability.

Some examples of operating criteria for reliable designs are

- 1) The unit will normally provide power for its auxiliaries through transformers connected to the generator bus.
- 2) 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 auxiliaries 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 auxiliaries system are expensive, the application and protection of the equipment should be coordinated. Some examples of design criteria that apply to equipment application are

- 1) The auxiliaries power system steady state voltage regulation should not exceed industry standards.
- 2) 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.

- 3) 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.
- 4) The horsepower rating of the motors should be coordinated with the requirements of the driven load (see Section 11.).
- 5) Any motor, NEMA frame size 440 and larger, should be capable of accelerating its load with 85% of rated motor nameplate voltage at the motor terminals (see ANSI C50.41-1982 [B2]¹). This criterion can be more restrictive than 3.2.5(2). 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.

3.2.6 Maintenance

The design of the auxiliaries 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 auxiliaries 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 auxiliaries 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.

Some examples of design criteria for plant expansion are

- 1) The overall design should provide for flue gas desulfurization equipment.
- 2) The unit auxiliaries and station service transformers should have a specified reserve capability.
- 3) The unit auxiliaries and station service transformers should have provisions for future forced-cooled ratings.
- 4) A specified number of spare switchgear cubicles should be provided.
- 5) Space should be provided in the physical design for connection of future transformers to the generator and startup source overhead conductors.

Approaches may vary, but the planner is encouraged to make allowances for expansion, which, as history indicates, is inevitable.

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 auxiliaries system. Some major factors to be evaluated are discussed in 3.2. In this section, these factors are discussed in more detail as they apply specifically to auxiliaries system planning. A planning guide flow chart is presented in Fig 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.

¹The numbers in brackets, when preceded by the letter "B," correspond to the Bibliography in Section 3.5.

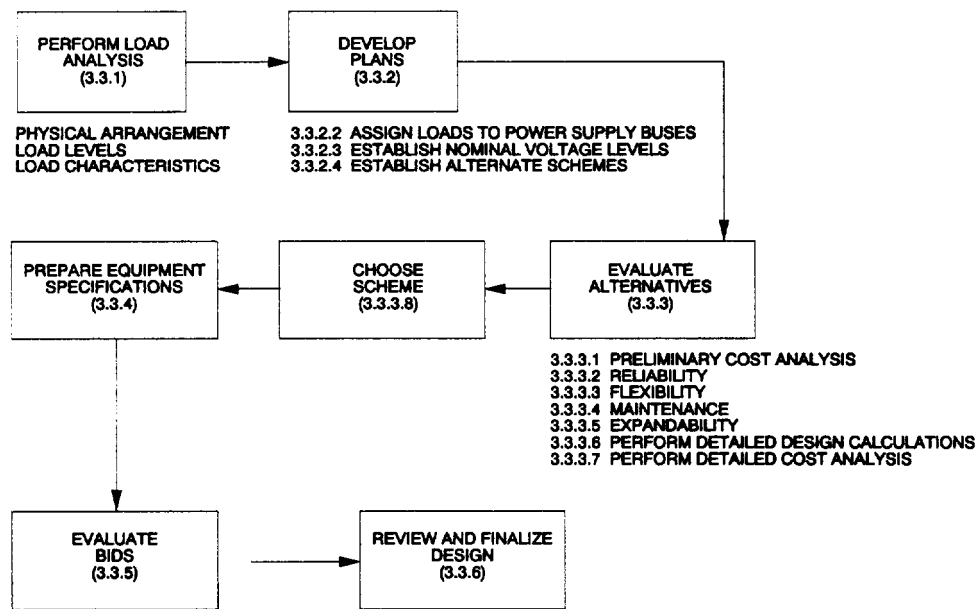


Figure 3.1 — Planning Guide Flow Chart

3.3.1 Load Analysis

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

- 1) *Physical Arrangement.* Data on cable lengths, special load requirements, and alternative locations for auxiliaries buses and equipment.
- 2) *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.
- 3) *Load Characteristics.* How the loads can and will be operated can influence the auxiliaries 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 Section 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.

- 1) *Operating Experience.* Examination of design and operating experience on existing plants will provide useful information in establishing acceptable plans for the auxiliaries 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.

- 2) *Accepted Industry Standards.* The schemes to be evaluated should conform to accepted industry standards. This provides some correlation between the auxiliaries power system designer and the equipment manufacturer. Industry standards can be obtained from ANSI², IEEE³, NEMA⁴, and other technical or environmental organizations.

3.3.2.2 Assigning Loads to Buses

In assigning loads to buses, the following criteria apply:

- 1) 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 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 auxiliaries bus.
- 2) 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.
- 3) 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.
- 4) 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.
- 5) 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 sections.

3.3.2.3 Establishing Nominal Voltage Levels

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

- 1) Total bus loads
- 2) Required short-circuit duty
- 3) Steady state voltage regulation
- 4) Motor starting voltage dips
- 5) Economics
- 6) Cable sizing

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

3.3.2.4 Establishing Alternate Schemes

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

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

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

⁴National 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 auxiliaries power system is shown in Fig 3.2 as a reference for nomenclature used in the remaining figures. The auxiliaries power system shown in Fig 3.2 receives its power from two sources: the unit source and the station source. The unit auxiliaries buses primary power supply is through a unit auxiliaries transformer (UAT) that connects via a tap to the generator bus between the generator circuit breaker and the unit transformer (UT). 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 stand-by or spare power source and sometimes may be used to supply station auxiliaries 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.

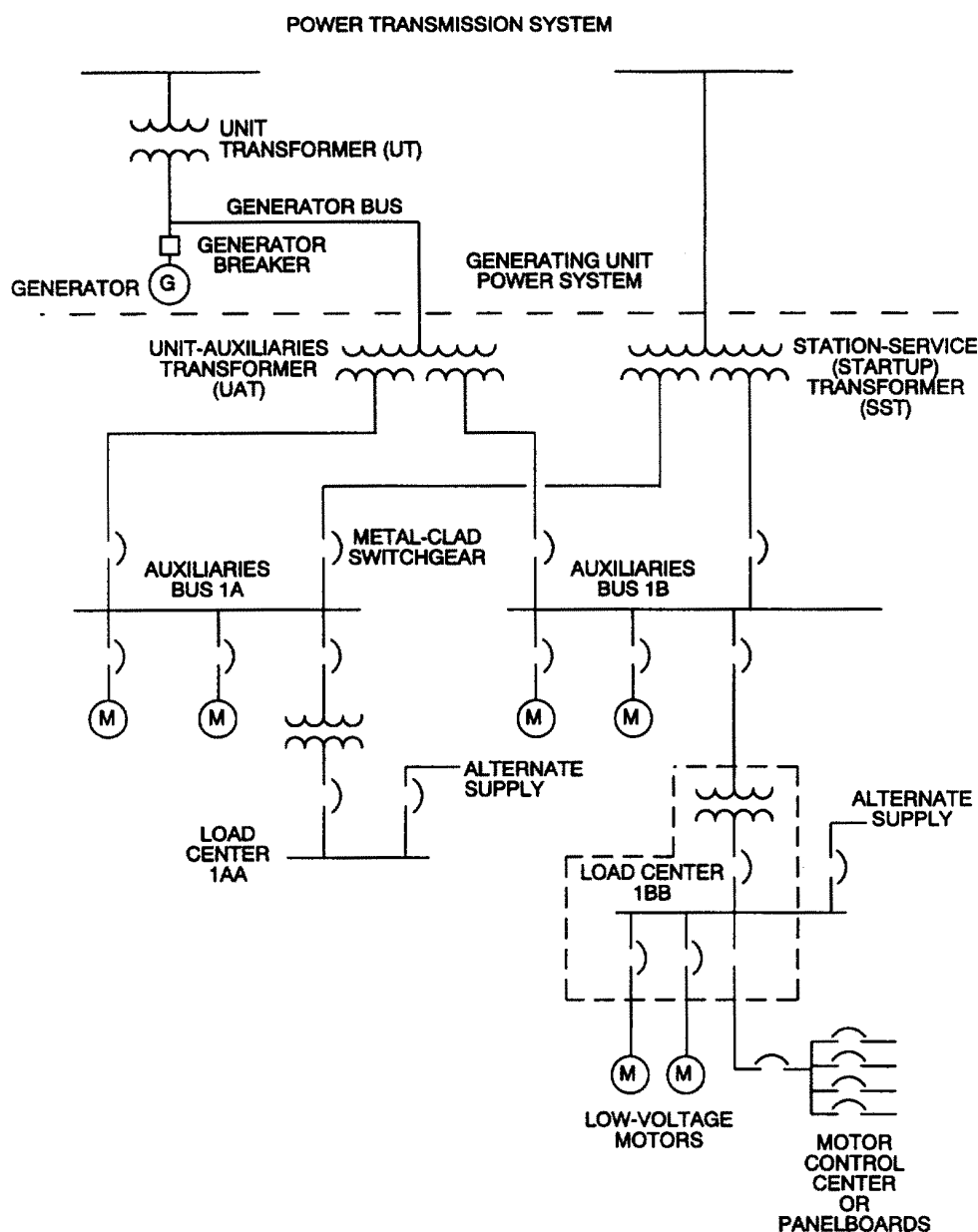


Figure 3.2 — Simplified Single-Line Diagram for Unit Connected Power System

The nominal voltage rating of the auxiliaries buses are usually 2.4, 4.16, 6.9, or 13.8 kV. These voltage levels are referred to as medium voltage. A line-up of metal-clad switchgears forms each auxiliaries (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.

Unit substations 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.

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

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 a 880 MW coal-fired unit is shown in Figs 3.3 and 3.4. This system is a four bus, unit connected, power supply system. Note that the unit auxiliaries 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 unit auxiliaries transformers, may avert an extended unit outage upon loss of any one bus or UAT. Fig 3.4 is an extension of Fig 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.

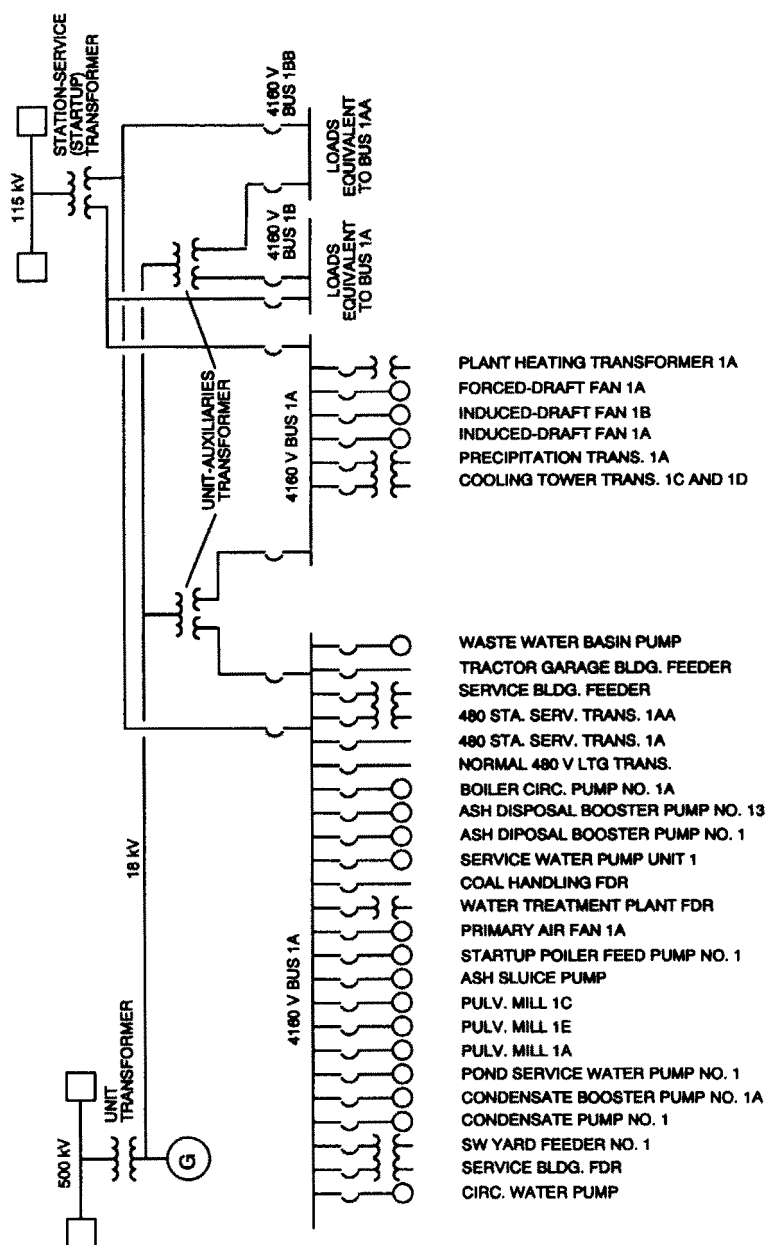


Figure 3.3 — Expanded Single-Line Diagram for 880 MW Coal Fired Unit

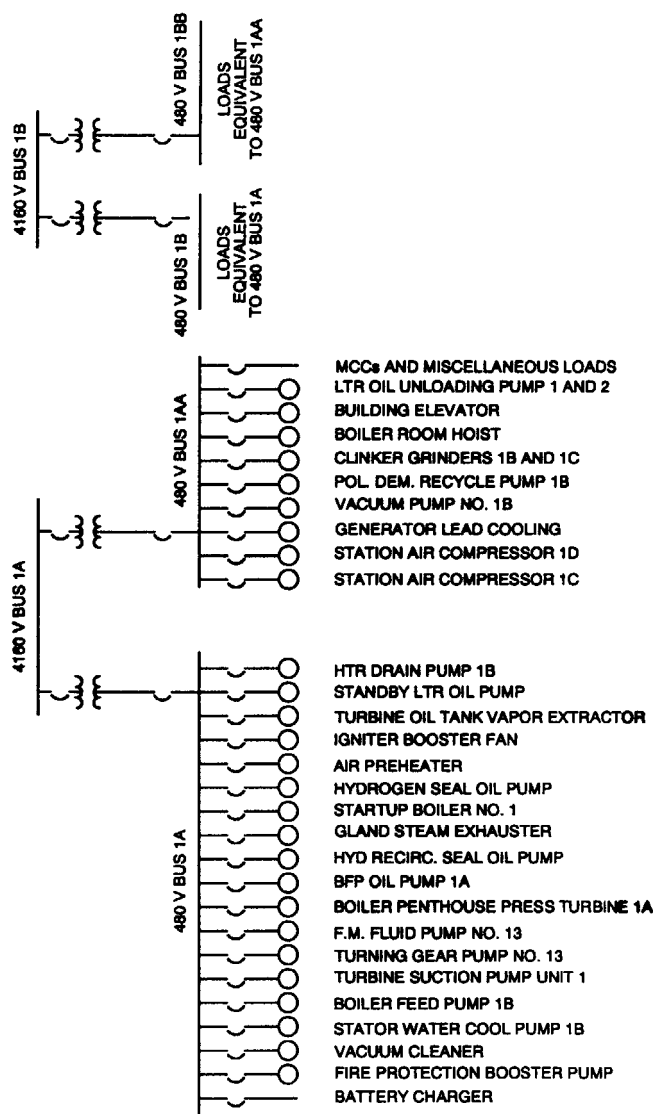


Figure 3.4 — Expanded Single-Line Diagram of the 880 MW Coal Fired Unit

3.3.2.4.3 Station Service (Startup) Transformer 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. Figs 3.5–3.10 illustrate the most common connections; however, other arrangements and variations do exist.

- 1) *Fig 3.5, Straight Bus.* This is perhaps 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.
- 2) *Fig 3.6, 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.

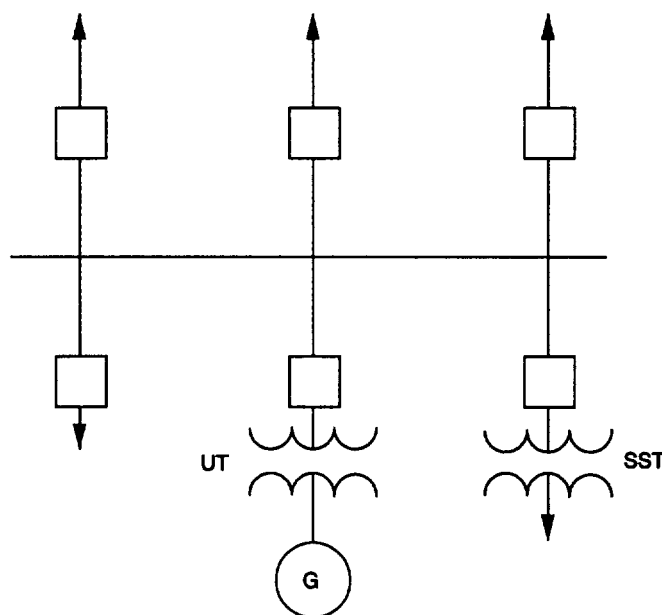


Figure 3.5 —Straight Bus

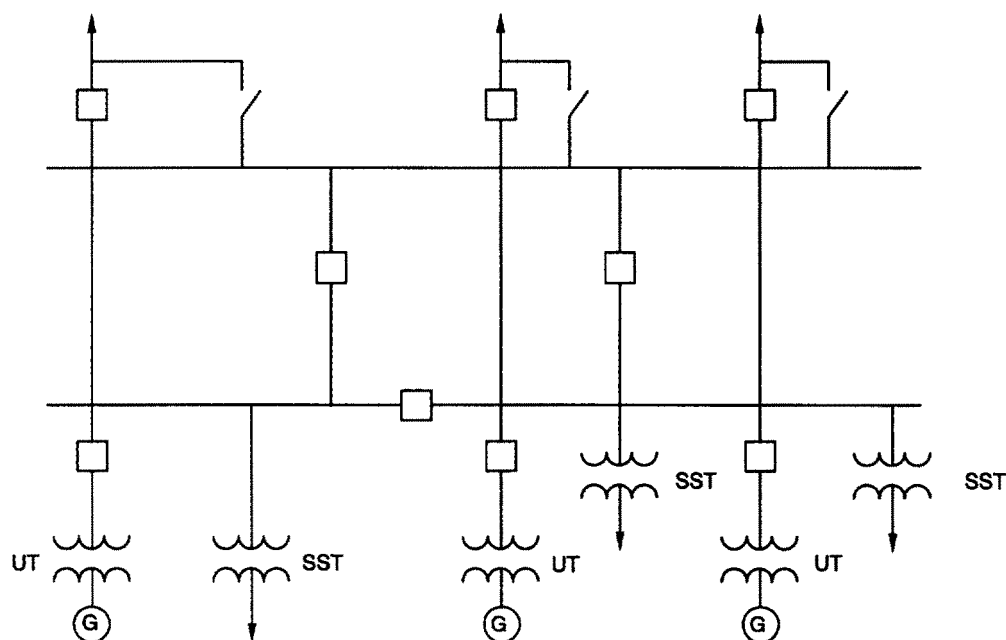
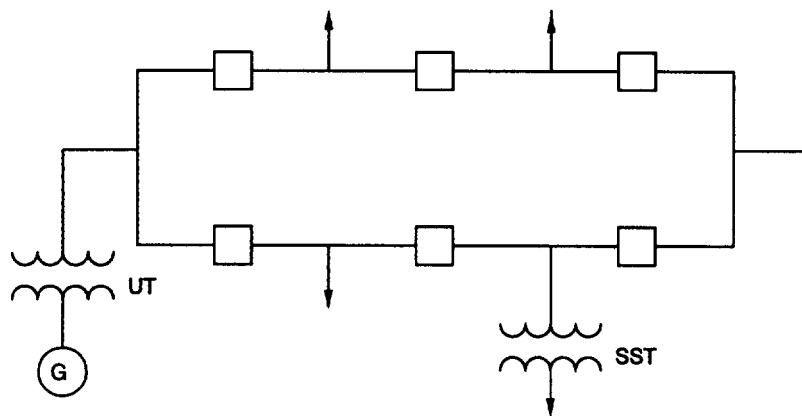


Figure 3.6 —Main and Transfer Bus

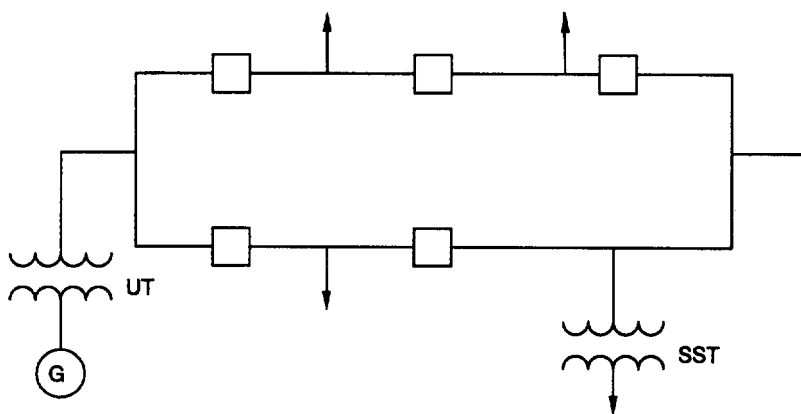
- 3) *Fig 3.7, Ring Bus.* Two ring bus connections are shown. The ring with separate SST bay position is secure against line faults, unless breaker failure occurs. The ring without separate SST bay position is exposed to faults of the line to which it is connected; however, it saves the cost and area 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.
- 4) *Fig 3.8, Breaker and 1/3 Bus.* This bus arrangement offers more security than the ring bus, since, for certain faults, breaker failure will not cause the SST to be tripped. Two possible connections are shown: one without

a bay position and one with a bay position. The economies of connecting the SST with a transmission line must be evaluated against the exposure to transmission line interruptions.

- 5) *Fig 3.9, 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* are options to be evaluated.



RING BUS, WITH BAY POSITION



RING BUS, WITHOUT BAY POSITION

Figure 3.7 — Ring Buses

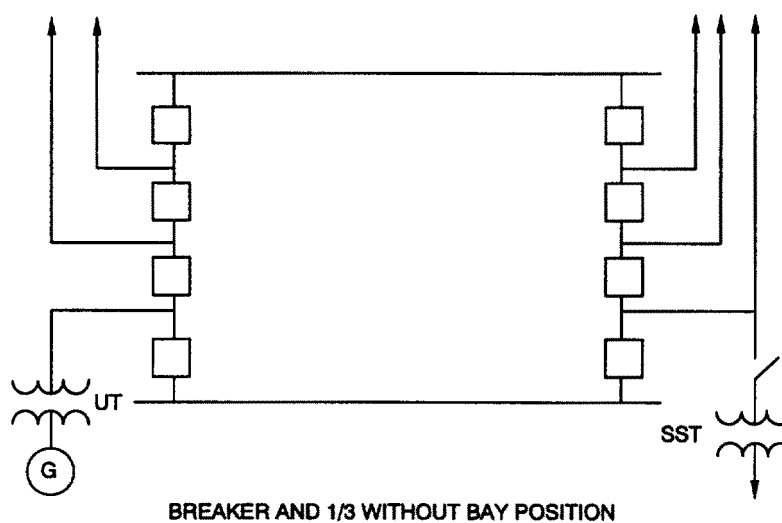
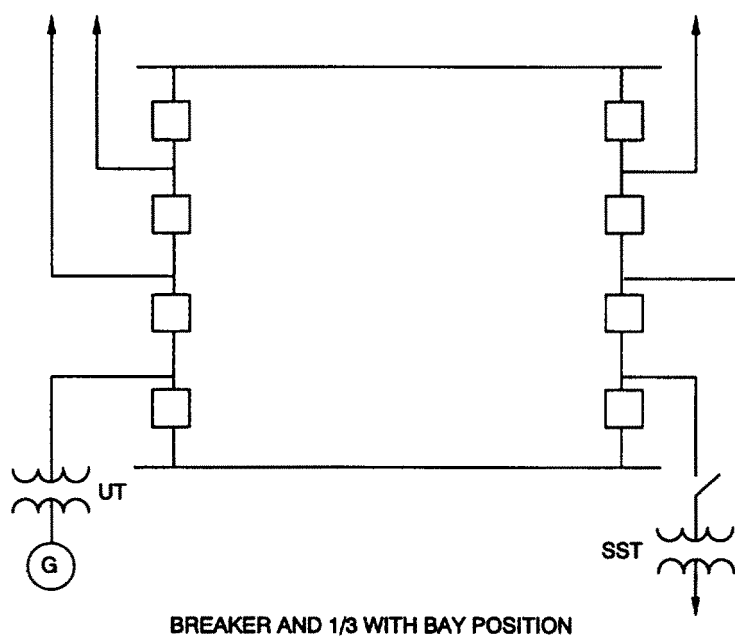


Figure 3.8 — Breaker and 1/3 Buses

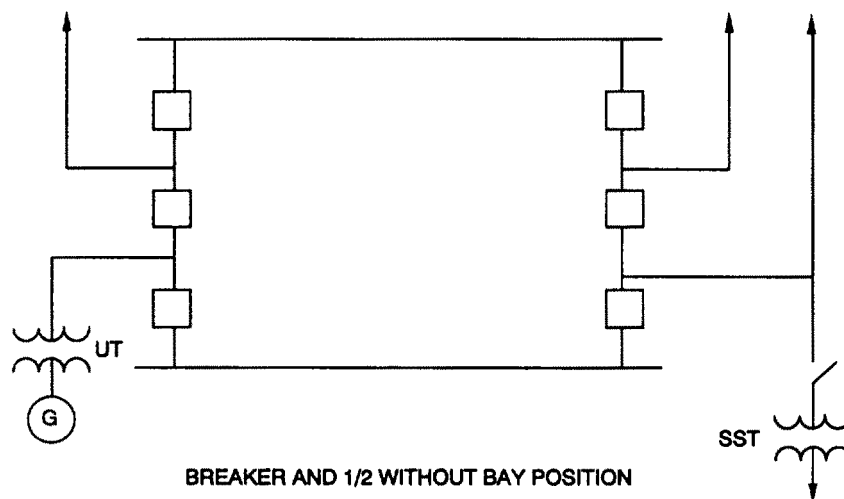
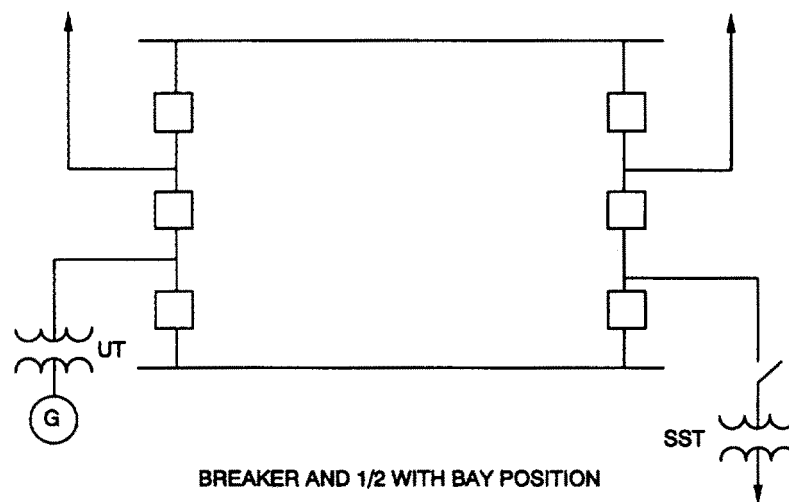


Figure 3.9 — Breaker and 1/2 Buses

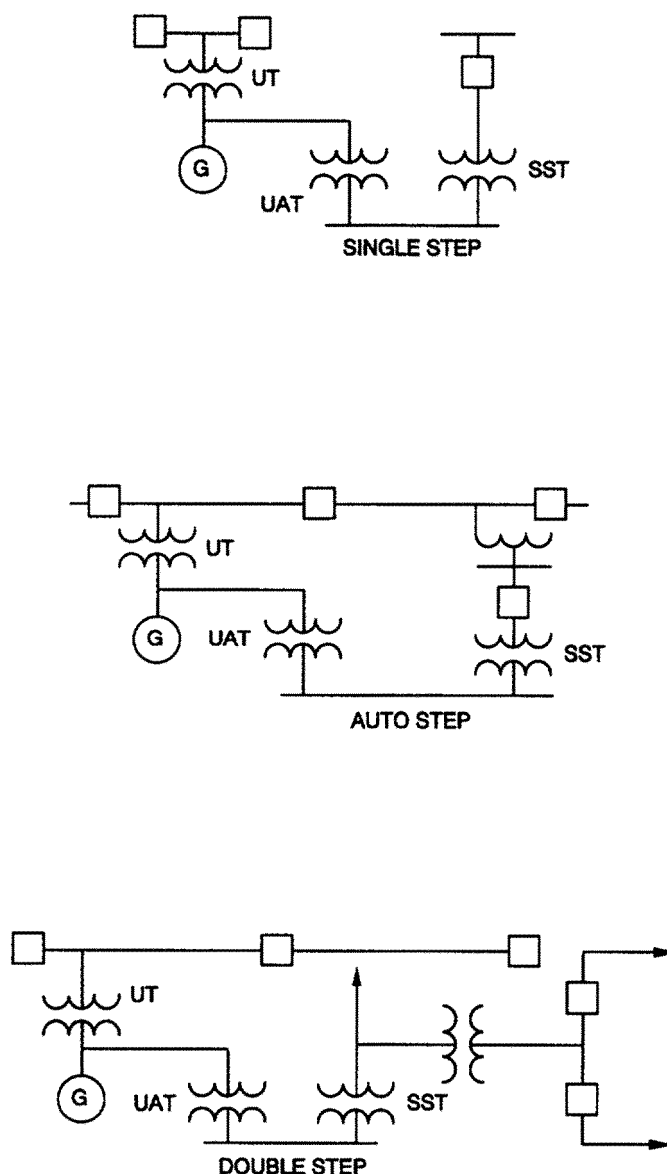


Figure 3.10 — Step Down Techniques

- 6) *Fig 3.10, Step-down Techniques.* Fig 3.10 illustrates step-down techniques that can be used to connect the utility power system to the auxiliaries buses. The single step is a common arrangement where voltage ratios are acceptable.

3.3.2.4.4 Unit Auxiliaries Transformer Connections

Figs 3.11–3.18 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.

- 1) *Fig 3.11, Three Winding Auxiliaries Transformers With Dual Auxiliaries Voltages and Common Auxiliaries 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, though the units lose some flexibility in that only one unit can be started at a time, or only one failed UAT can be spared.

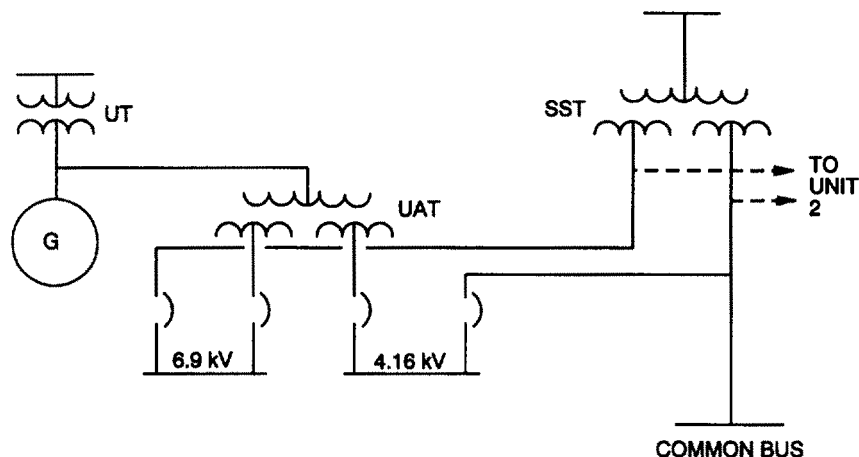


Figure 3.11 —Three Winding Auxiliaries Transformers With Dual Auxiliaries and Common Service Bus

- 2) *Fig 3.12, Three Winding Auxiliaries Transformers With Split Auxiliaries Buses.* This arrangement is similar to that of Fig 3.11, except that each secondary winding is connected to serve two auxiliaries 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.

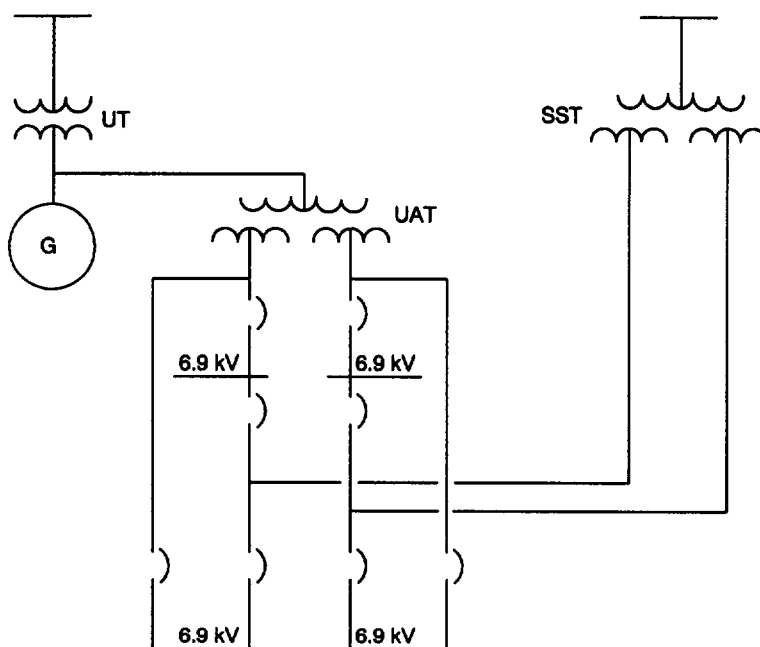


Figure 3.12 —Three Winding Auxiliaries Transformers With Split Auxiliaries Bus

- 3) *Fig 3.13, Two Winding Auxiliaries Transformers With Split Auxiliaries Buses.* The scheme is similar to Fig 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 Fig 3.12 due to the two winding transformers.

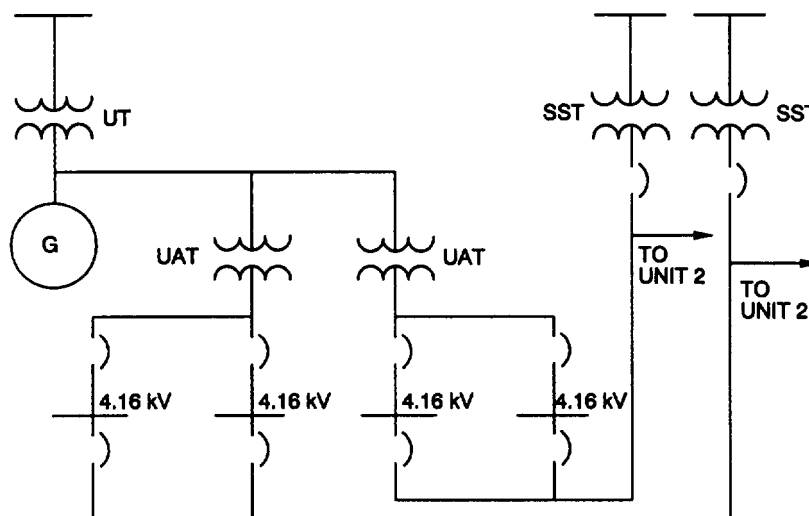


Figure 3.13 — Two Winding Auxiliaries Transformers With Split Auxiliaries Bus

- 4) *Fig 3.14, Dual Three Winding Auxiliaries Transformers With Dual Auxiliaries 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.

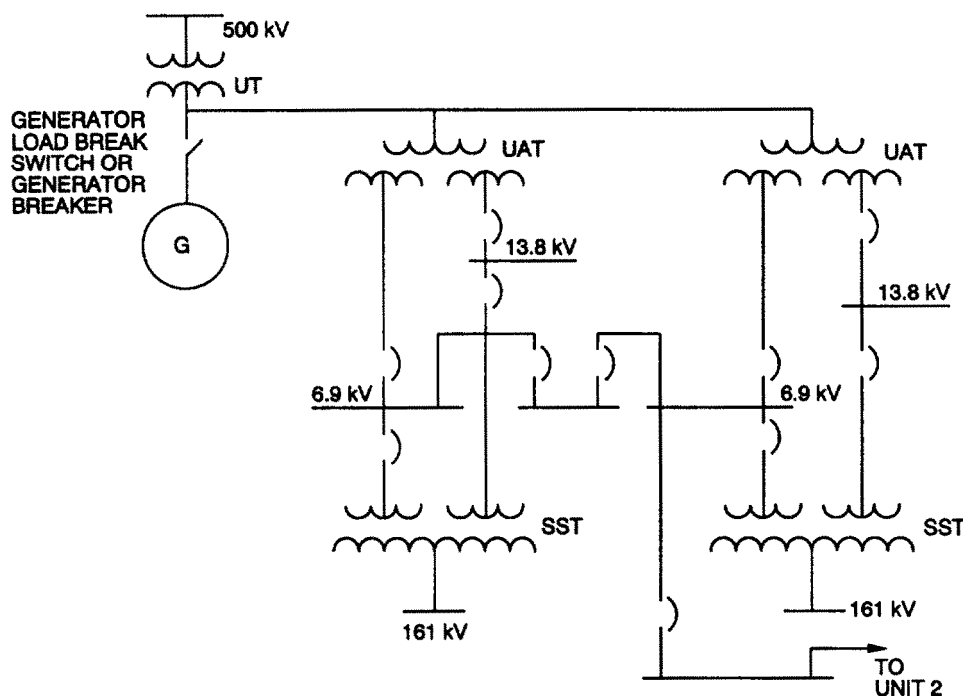


Figure 3.14 — Dual Three Winding Auxiliaries Transformers With Dual Auxiliaries Voltage

- 5) *Fig 3.15, Two Winding Auxiliaries Transformer With Dual Auxiliaries Voltage, Intermediate Auxiliaries Transformer, and Common Auxiliaries Bus.* This scheme is unusual but might be used for a large system serving multiple units. The auxiliaries transformers supply voltage to an auxiliaries (medium voltage) substation. The 13.8 kV buses serve large motors. Smaller motors are supplied from the 4.16 kV buses. Note that alternate sources are provided from other units with appropriate switching. The common buses supply loads common to all units. The disadvantage of this scheme is its complexity. It illustrates how quickly a system can become complex when multiple supplies are provided. The economic advantages and overall system reliability depend on each application.

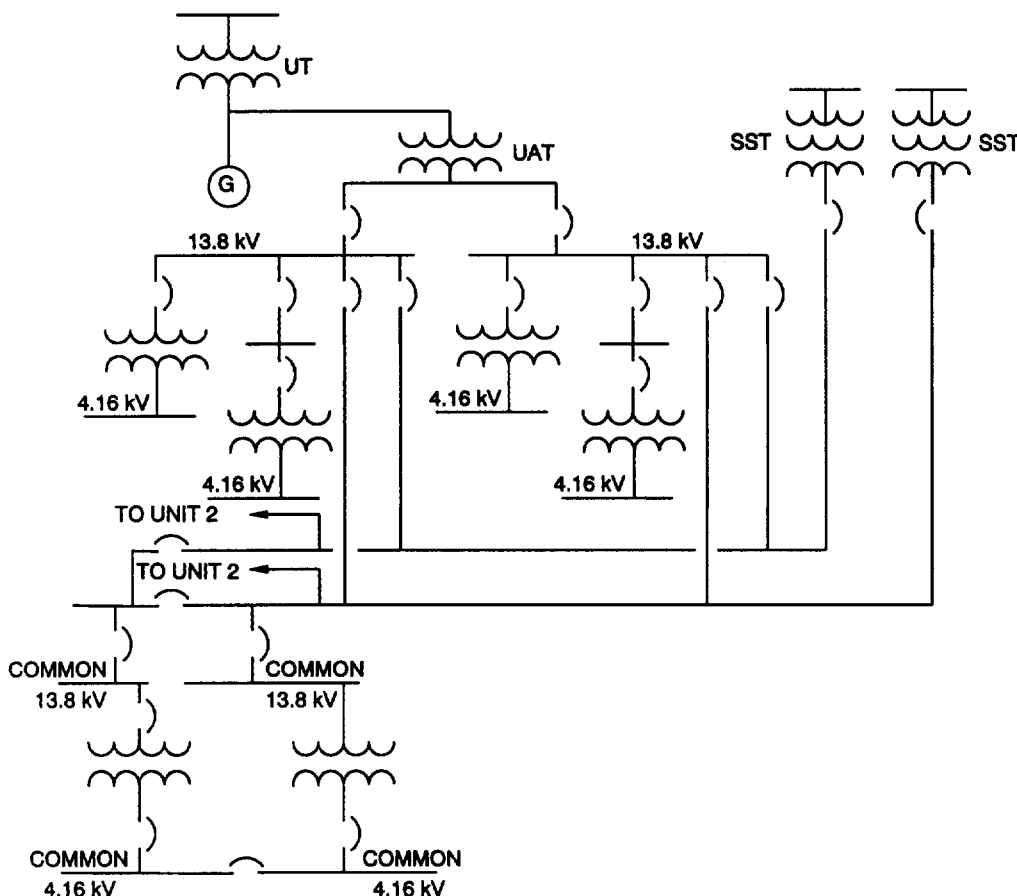


Figure 3.15 — Two Winding Auxiliaries Transformer With Dual Auxiliaries Voltages, Intermediate Auxiliaries Transformers and Common Auxiliaries Bus

- 6) *Fig 3.16, Three Winding UAT — Delta Tertiary SST With Split Auxiliaries Buses and Dual Auxiliaries Voltages.* This scheme is similar to the other three winding auxiliaries transformers split auxiliaries 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.

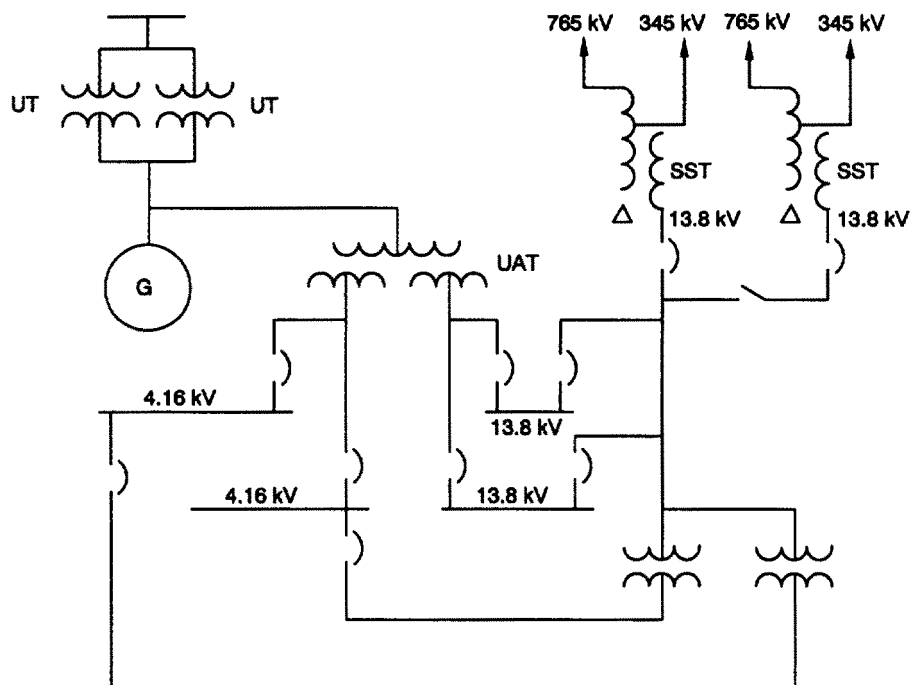


Figure 3.16 —Three Winding UAT — Delta Tertiary SST With Split Auxiliaries Buses and Dual Auxiliaries Voltage

- 7) *Fig 3.17, 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 auxiliaries served through the UT and UAT. By eliminating the SST, there is no need to transfer the auxiliaries 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 additional UAT.

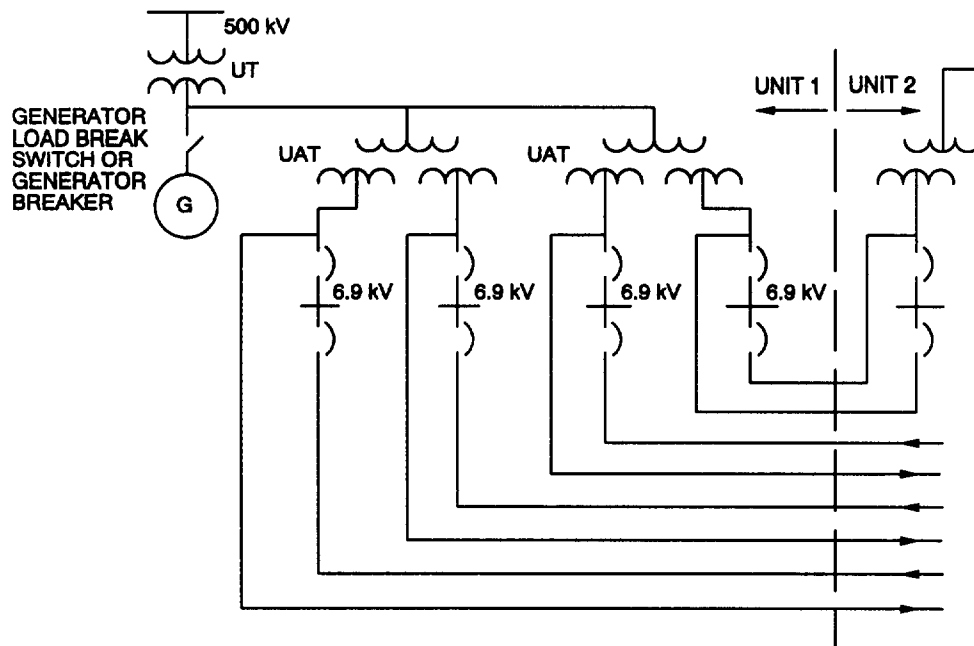


Figure 3.17 — Three Winding UAT With Generator Load-Break Switch or Generator Breaker

- 8) *Fig 3.18, Supply From Station Service Only.* In this scheme, the UAT is eliminated, and the auxiliaries are served completely through the SST. In this example, a number of SST 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 auxiliaries from a UAT to an 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 load of the auxiliaries. 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.

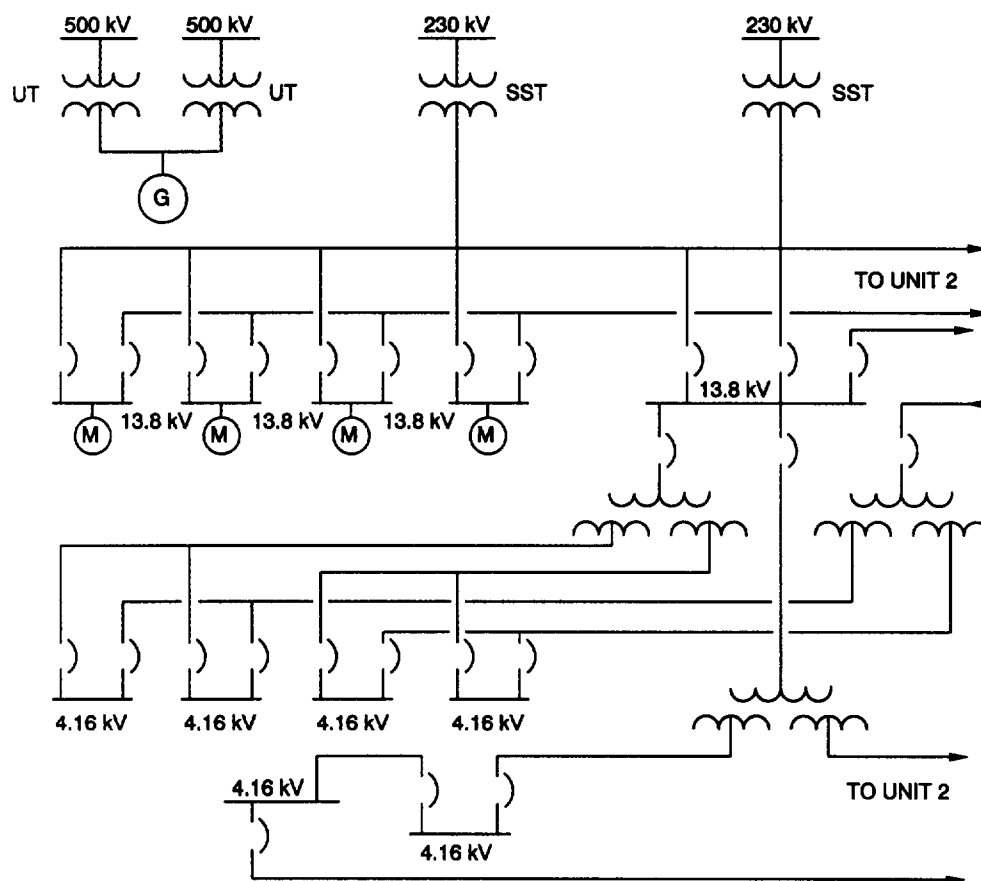


Figure 3.18 — Supply From Station Service Only

Once the alternative schemes have been considered, the designer is then ready to begin evaluating them in order to select the optimum design.

3.3.3 Evaluating the 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 below.

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 the effect on the auxiliaries 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 data bases 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 auxiliaries 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 must be given serious study.

3.3.3.4 Maintenance

While maintenance is largely the responsibility of plant personnel, the auxiliaries systems 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 auxiliaries 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.

3.3.3.5 Expandability

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

- 1) Larger mechanical loads than anticipated
- 2) Coal and ash handling facility modifications
- 3) Efficiency and availability improvements (i.e., balanced draft conversions)
- 4) Unit cycling requirements — electric drives for existing turbine-driven load (i.e., boiler feed pump)
- 5) Environmental — precipitators and flue gas desulfurization

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 judgement 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 such as transformer MVA rating and impedance, breaker ratings, etc. This is an integral input into the equipment specifications.

3.3.3.7 Detail 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 capital, maintenance, and operating costs. Note that maintenance costs and operating costs are distinct, since 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. 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 auxiliaries 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 auxiliaries 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 section 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 load flows. For a more accurate representation, these load flows should be run with the station service load. If the station service load is neglected, then regulation must 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 SST is 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 auxiliaries bus short-circuit rating, the required transformer impedance(s) can be determined. Of course, this impedance must satisfy voltage regulation requirements as noted in 3.4.1.1.

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 from the SST to the UAT and vice versa. Phase angle differences are both steady state and transient in nature. Transient phase angle differences in the auxiliaries 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. Section 4. discusses auxiliaries bus transfer. The steady state phase angle difference between the UAT and the SST is caused by either (1) the transmitting of power through the power system or (2) three phase transformer winding connections.

- 1) The generating unit and SST(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 UT connected to 500 kV and the SST connected to 115 kV. These two transformers may be connected at the generating unit by an auto or step-down transformer, or they may only be connected by virtue of the interconnected transmission system. The maximum angle difference between the generating unit and the SST(s) for the worst power flow is determined by the transmission planning engineer by running load flow cases. The power system should be designed and the equipment purchased to be capable of tolerating the maximum angle determined, since this angle cannot be judiciously adjusted to zero.
- 2) 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 Section 4.), the phase angle difference between the two sources must be 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 Fig 3.19.

3.4.2 Generator

- 1) *MVA Rating.* The MVA rating of the generating unit has a direct influence on the design of auxiliaries systems. In general, the larger the main generator, the larger the power consumed by the auxiliaries system. In the past, coal-fired unit auxiliaries power systems consumed 5% to 8% of generator output. However, with the rapid increase in stringent environmental laws, the power consumed by auxiliaries power systems has risen in some coal-fired units to 10% to 12% of the generator rating. The increase in the auxiliaries system capacity has also resulted in the design of the auxiliaries system becoming more complex. As the MVA rating of the unit increases, the desired reliability of the unit increases correspondingly. This is because (1) the larger units are intended for base load operations, and (2) the initial cost of the unit and energy replacement costs are very high.

- 2) *Voltage Rating.* As stated in ANSI C50.13-1977 [B1], “generators shall operate successfully at rated kilovoltamperes (kVA), frequency, and power factor at any 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.

If this is true, it may necessitate increasing the number of auxiliaries 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 UT regulation, tap settings, power system reactive power requirements, transmission system voltage schedules, and the coordination of these with the unit auxiliaries, station service, and load center transformer tap settings.

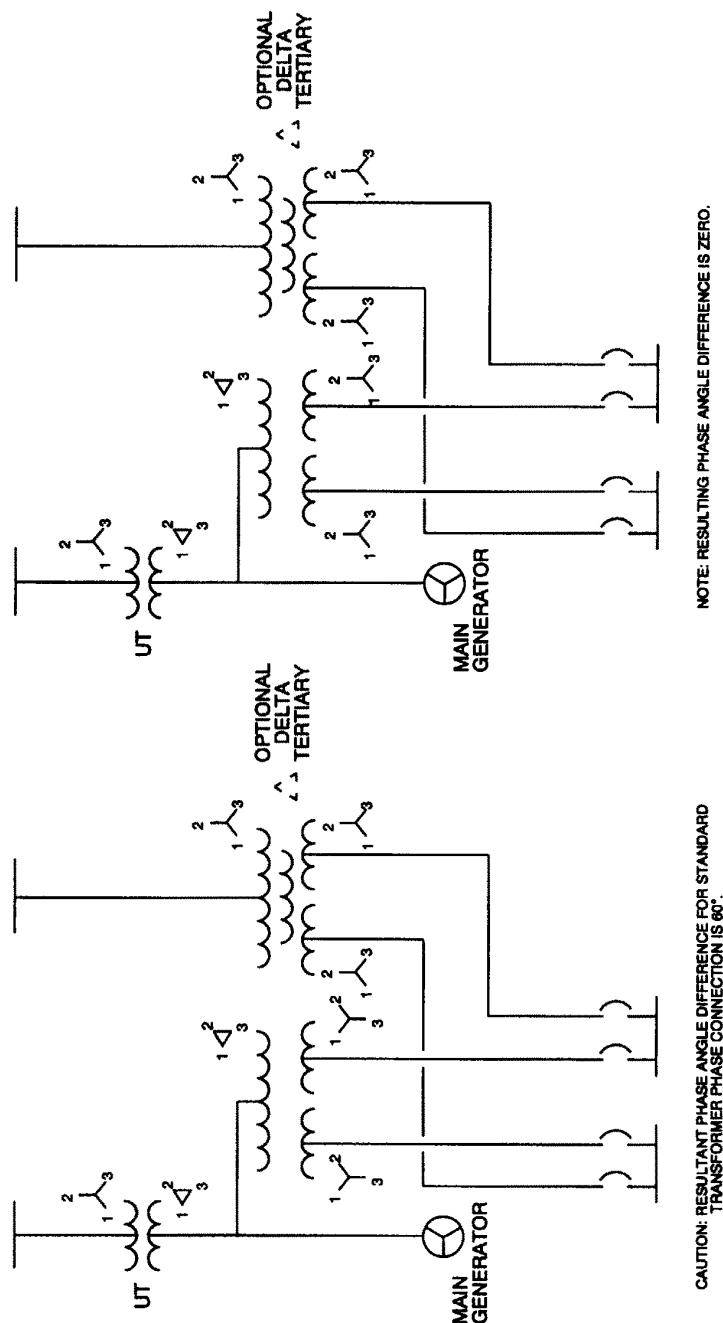


Figure 3.19 — Phase Shift Due to Three Phase Transformer Winding Connections

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 Fig 3.14). This decision may not rest solely on the auxiliaries power supply system requirements. However, it does have a major impact on the auxiliaries 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 auxiliaries system. In the absence of the station service transformer, the auxiliaries 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 auxiliaries system flows through two transformers: the UT and the UAT. 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 UT. The tap of the UT is normally set for the operation of the transmission system and not to supply the auxiliaries.

3.4.4 Station Service Transformer Connections

The station service transformer connection requirements are influenced by the following factors.

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 auxiliaries 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, 4.16, or 2.4 kV. Another option is to use the tertiary of an existing autotransformer as the source of the desired voltage (see Fig 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 auxiliaries 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 10% and 7.5% for three and two winding transformers respectively (see ANSI C57.12.00-1987 [B3]). The difference in tolerance can have a significant effect on the preliminary design phase of the auxiliaries power systems.

In the preliminary design, the exact impedance of the auxiliaries 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 auxiliaries bus load, or the change in design boundary constraints.

3.4.5 Transformer Duty

The UAT and SST 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 auxiliaries and starting of larger motors, etc. Since a UAT 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 UAT 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 Section 9.

3.5 Bibliography

- [B1] ANSI C50.13-1977 (R 1989), American National Standard for Rotating Electrical Machinery — Cylindrical Rotor Synchronous Generators.
- [B2] ANSI C50.41-1982, American National Standard for Polyphase Induction Motors for Power Generating Stations
- [B3] IEEE C57.12.00-1987, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (ANSI).
- [B4] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).
- [B5] IEEE Std 141-1986, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (ANSI).
- [B6] IEEE Standard 505-1977, IEEE Standard Nomenclature for Generating Station Electric Power Systems (ANSI).
- [B7] Beeman, D., ed. *Industrial Power Systems Handbook*, McGraw-Hill Book Company.
- [B8] Cavallaro, S. “Application of Generator Circuit Breakers to Nuclear Power Stations,” IEEE PES Winter Power Meeting 1975, New York, NY, C75 191-2.
- [B9] Nunley, J. W., Voyles, J. L., Apparatus, J. C., and Bonk, G. J. “Optimal Application of Major Electrical Equipment to Generating Station Auxiliary Systems,” *IEEE Transactions (PAS)*, Vol. 92, Jan./Feb. 1973, pp. 222–229.
- [B10] Reed, G. R. and Webster, D. R. “Design of AC Auxiliary Power Distribution Systems for Large TVA Thermal Power Generating Plants,” IEEE PES Winter Meeting, 1975 New York, NY, T75 081-5.
- [B11] Reiman, R. J. and Hatstat, C. A. “Selection of 6.9 kV voltage for East Bend Station Auxiliaries,” *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-96, Nov./Dec. 1977, pp. 1882–1891.
- [B12] 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.
- [B13] Sprouse, M. N. “Electrical Design Practice — TVA Fossil Fueled Generating Plants,” IEEE PES Winter Power Meeting 1970, New York, NY, 70TP 214-PWR.

4. Startup and Shutdown Requirements

4.1 Introduction

Auxiliaries 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. After a unit generator has been synchronized to the system and partially loaded and transfer has taken place, service to its auxiliaries is supplied normally from the unit generator terminals through a unit auxiliaries transformer. This supply is identified as either the unit auxiliaries 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 auxiliaries. They also should provide margin for future load growth. Quality of power is an important consideration that must 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 auxiliaries. The station service system must provide lubrication and sealing oil during and after coastdown, remove residual heat, purge the boiler, maintain condenser vacuum, and provide service to other critical components and protective systems.

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 has been 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 auxiliaries 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 auxiliaries 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 auxiliaries to the common station service system during the startup of another unit's auxiliaries. Instead of designing a system to supply auxiliaries 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 auxiliaries 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, and electric boilers not used during full-load operation. 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 auxiliaries 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 must 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 auxiliaries required during an automatic transfer of the buses from the normal to the startup/shutdown source. 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 auxiliaries that may be added after the plant is placed in service. An acceptable margin for future loads should be included in transformer and feeder cable capacity and space should be provided for switchgear and motor control center additions. Short-circuit withstand capability of switch-gear 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.

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 auxiliaries may cause equipment damage, the repair of which will delay restart and incur replacement power costs. For these reasons, the cost of an alternative power source is usually 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 auxiliaries (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 V/Hz rating can cause equipment damage.

4.3.3 Phasing

When an alternative source is available continuously to accept a transfer of the auxiliaries 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 auxiliaries 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 5%. Percent unbalance is defined (see NEMA MG 1-1987, 14.34B [B6]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 MG1-1987, 22.42 [B6]). 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 auxiliaries. The normal source is usually a transmission or distribution system voltage that will be transformed onsite to a lower utilization voltage. ANSI C84.1-1989 [B2] establishes voltage ratings and recommends that source voltages should have a sustained value of between 98% and 105% of the nominal voltage, corresponding to Range A. It should be noted that these values are recommendations only, and the required range is a function of the specific design of the auxiliaries 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 Section 5.

Source voltages may have transient values outside the above range. Transient overvoltages caused by lightning or switching must 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 pu. This may occur if the dead-bus time of the transfer exceeds 4–6 c. Dead-bus time is the time in which the auxiliaries service bus is

⁵The numbers in brackets, when preceded by the letter “B,” correspond to the Bibliography in Section 4.10.

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 auxiliaries service systems should always be used for calculating the electrical system performance of the final plant design.

4.4 Startup/Shutdown Power Supply Arrangements

Arrangement and configuration of connections selected to provide a source of power for startup/shutdown of the unit depend on various factors. Typical considerations include availability of sources, quantity and arrangement of auxiliaries buses, the number of units at a site, the proposed normal auxiliaries power supply, and equipment reliability and cost. Although power supply arrangements have been discussed in Section 3., four basic arrangements are briefly introduced to emphasize commonly-used station service system designs.

4.4.1 Auxiliaries Transformer and Generator Load-Break Switch/Generator Circuit Breaker

A load-break switch is installed in the generator leads between the unit generator and the unit auxiliaries transformer, as shown in Fig 4.1. During plant startup/shutdown, the load break switch is open, and the power supply direction is from the switchyard through the generator transformer to the unit auxiliaries transformer. When the generator comes into synchronism with the switchyard source, the generator load-break switch can be closed, thereby connecting the generator to the switchyard. No bus transfers are required, making the scheme relatively simple. One disadvantage of the scheme is that a fault on the generator leads, in the generator, or in any transformer connected to the generator leads must be cleared by the switchyard circuit breakers, thereby causing a unit blackout. Some improvement can be made by substituting a generator circuit breaker with an isolating switch for the load-break switch. The generator breaker would clear generator faults without interrupting power to its auxiliaries.

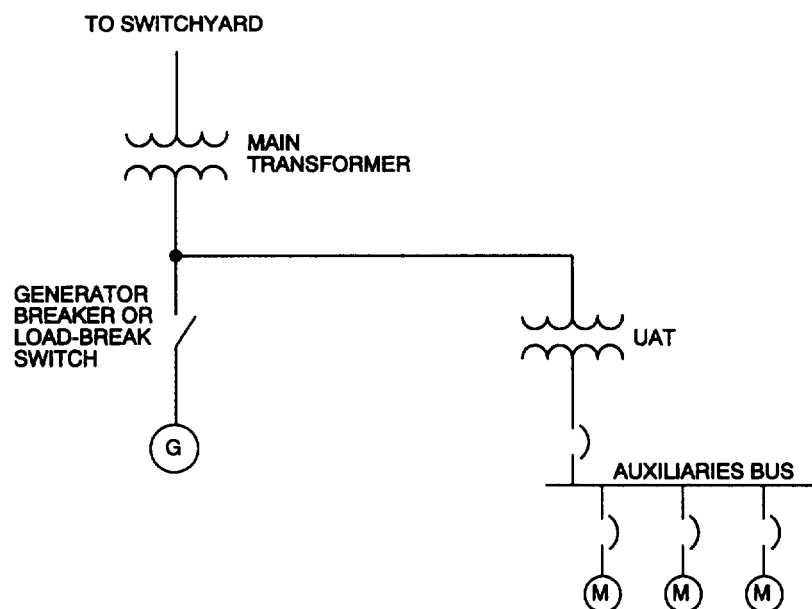


Figure 4.1 — Typical Generator Load-Break Switch or Generator Circuit Breaker Arrangement

The use of a generator load-break switch or generator circuit breaker may require special protection. If the generator is the ground source, then the system made up of the low side of the unit transformer, interconnections (bus), and unit auxiliary transformers becomes ungrounded when the switch or breaker is open. A protection scheme such as the one discussed in Section 7.3.4 for ungrounded systems should be considered.

4.4.2 Station Service Transformer

The power supply to the auxiliaries is from a station service transformer connected to the switchyard, as shown in Fig 4.2. The station service transformer supplies the auxiliaries during normal, startup, and shutdown operation. The switching of this transformer is performed by a high-voltage breaker in the switchyard. Due to the fact that loss of this transformer will leave the plant auxiliaries without power, this scheme is not commonly used. Another consideration is that any voltage disturbances on the transmission system will appear in direct proportion on the auxiliaries system.

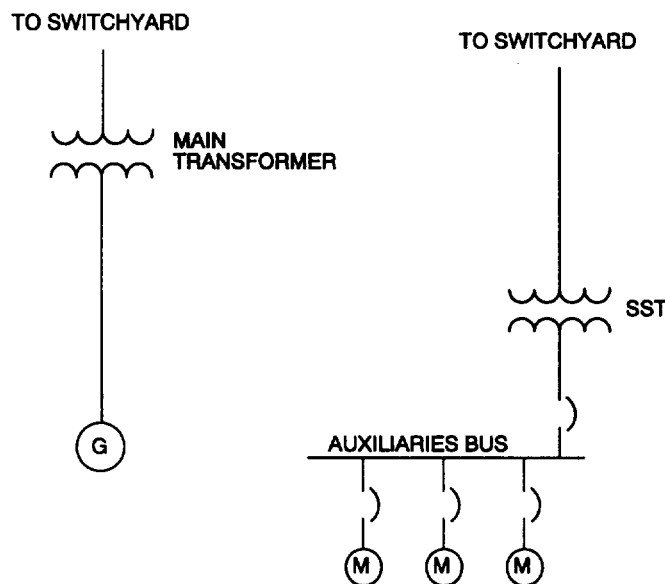


Figure 4.2 — Typical Station Service Transformer Arrangement

4.4.3 Station Service Transformer and Auxiliaries Transformer

In this scheme, which is the most common, there are two separate source connections to the unit auxiliaries bus, as shown in Fig 4.3. One connection is to the station service transformer for startup/shutdown operation. The other connection is to the unit auxiliaries transformer for normal operation. The disadvantages of this scheme are increased cost due to additional equipment, increased complexity of the relaying, and coordination required for transfer of the auxiliaries bus between the two connections. However, a dual power supply offers greater availability and reliability. Also, there will be fewer losses during plant operation because power is supplied directly from the generator to the auxiliaries bus through one transformer only. In Fig 4.2, power is supplied through more than one transformer to reach the plant auxiliaries, with correspondingly greater losses.

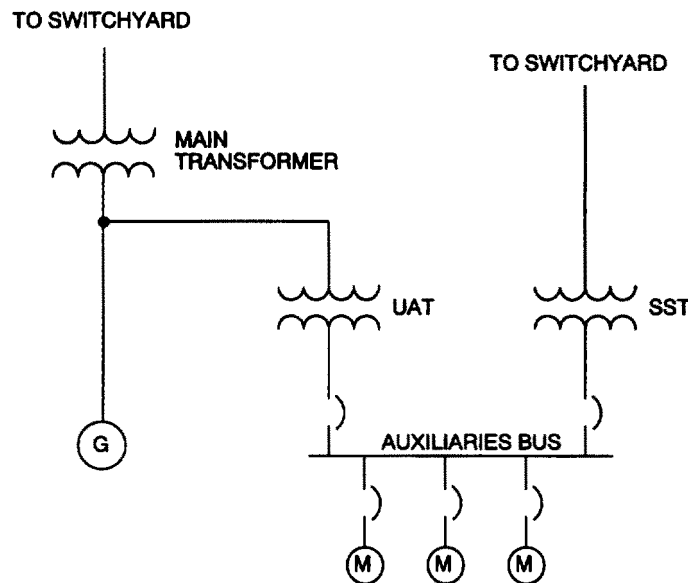


Figure 4.3 — Typical Station Service Transformer and Unit Auxiliaries Transformer Arrangement

A comparison of this scheme with the scheme that incorporates a generator breaker (shown in Fig 4.1) would be required to determine the more economical and reliable configuration. A major advantage of the above scheme may occur in multiple-unit plants if the station service transformer can be shared between units. Utilization of the generator breaker in Fig 4.1, in conjunction with using the main transformer as a startup/shutdown source for the auxiliaries, can eliminate the requirement for a station service system with its associated costs. However, during outages of single-unit plants, a smaller station source is still required for “house” loads to permit outages of the bus/cable system connecting the generator and the unit transformer.

4.4.4 Auxiliaries Transformer and Onsite Power Source

The startup/shutdown power source for the auxiliaries is an onsite source connected to the auxiliaries bus, as shown in Fig 4.4. After startup, the normal source of power to the auxiliaries is the UAT. The startup/shutdown source is usually a combustion-turbine or hydro-driven generator, supplying auxiliaries only during startup or shutdown. This scheme is not common on large units due to the size of the onsite source that would be required (i.e., auxiliaries requirements could be 10% to 12% of the unit generator output). However, in cases where the onsite source could provide an additional function, such as supplying peaking power, it may prove practical. When the above types of sources are used for startup, it should be noted that if the startup requires a large motor or a number of large motors to be started simultaneously, the size of the generator necessary should be reviewed in conjunction with the motor reactive power requirements, which will be much larger during starting.

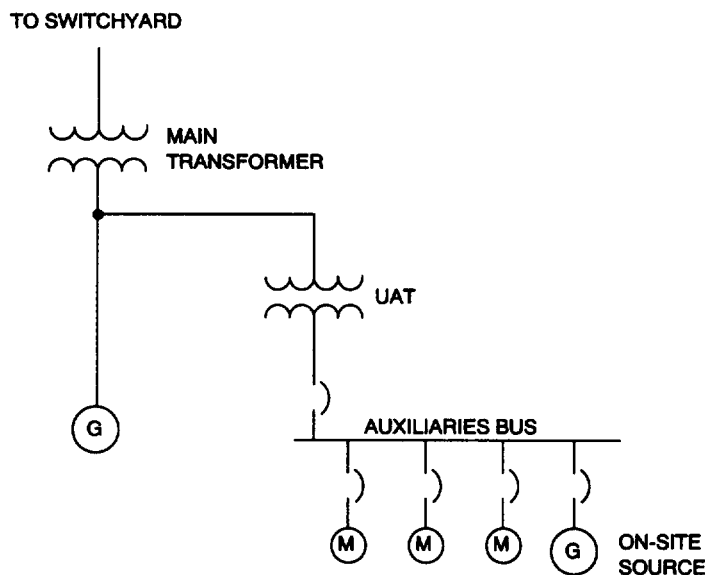


Figure 4.4 —Typical Startup/Shutdown Onsite Source Arrangement

The above scheme applies to onsite sources providing both startup and shutdown power requirements. The use of an onsite source (standby generator) to provide power to protective or emergency loads during loss of normal station power is discussed in 4.9.

4.5 Auxiliaries Equipment Supply Arrangements

In conjunction with selecting startup/shutdown power supply arrangements, proper design in the location and arrangement of auxiliaries equipment and buses will increase the safety and reliability of the system. The arrangement should include coordination of equipment requirements for both normal and startup/shutdown operation.

4.5.1 Equipment Separation for Reliability

Most units incorporate the use of duplicate and standby auxiliaries in the system design to ensure that, if one component is out of service due to failure or maintenance, its duplicate or standby will be available to allow unit operation at either full or reduced power. In addition, the use of duplicate equipment limits the supply system requirements and allows sequential starting of a series of smaller loads, which assists in bus voltage regulation. An example of duplicate or standby equipment is the use of two or three motors, each rated to carry half of the load versus one motor rated to carry the full load.

Duplicate equipment required for startup/shutdown should be served from separate buses with separate power sources or feeders, if possible. This ensures that a loss of one bus will not affect duplicate motors and equipment on the other. At the same time, duplicate loads required for normal operation should also be served from separate buses. The final design should result in multiple and relatively separate auxiliaries bus systems. The extent to which plant design will meet these criteria is dependent on evaluation of reliability gained versus added cost.

4.5.2 Equipment Separation for Protective Systems

In addition to bus separation of duplicate or standby auxiliaries loads required for both normal and startup/shutdown operation, those loads required for protective systems should also be served from separate buses or sources to achieve as much reliability as possible. Protective systems, as defined in 4.7, are those services required, especially during an unscheduled shutdown, to shut the unit down in a safe, controlled manner.

4.6 Auxiliaries Bus Transfers

During startup of the station, the unit auxiliaries bus (or buses) is typically powered from the station service system. When the unit generator has been started, partially loaded, and then synchronized with the station service system, the bus is transferred from the station service system to the unit auxiliaries system, thus obtaining its power from the unit generator. Transfer is made by closing the auxiliaries system circuit breaker, momentarily paralleling both sources, and then tripping the station service system breaker. To shut down a unit, the reverse procedure is followed. In addition to scheduled transfers during startup and shutdown, the auxiliaries bus supplying protective system loads should have the capability of being transferred to the station service system or another alternative source when there is a sustained electrical disturbance on the unit auxiliaries system. This disturbance may be due to an undervoltage condition, a fault condition, or a generator or turbine trip. A properly-designed scheme for both scheduled and unscheduled transfers will minimize both unit outage time and possible damage to equipment during transfer.

It should be noted that there may not be one “best method” of transfer, and that the transfer scheme or combination of schemes selected may require a compromise based on unique equipment requirements and conditions existing at a specific generating station.

The common types of transfers may be divided into two general categories: manual and automatic. Transfers may be categorized in other groupings, but, for purposes of this guide, this division is used with the subsequent definitions. It should be noted that the exact nomenclature of the different transfers discussed in this section may not be identical to the nomenclature used in the reference material, but the type of transfer will be readily distinguishable by its design characteristics and sequence of operation.

As an example, the transfer scheme identified as a “residual voltage transfer” in this guide is identified as a “selective time delay transfer” in [B12].

4.6.1 Manual Transfer

Manual transfer is initiated by an operator and is usually a scheduled transfer, such as during routine startup and shutdown operations. Transfer during startup is from the station service to the unit auxiliaries system. During shutdown, transfer is in the opposite direction. The transfer sequence for startup is as follows. With the station service (outgoing) source breaker connected to the auxiliaries bus, and after it has been checked for synchronism, the auxiliaries (incoming) source breaker is closed. Both sources are paralleled momentarily until the outgoing breaker is tripped. Tripping of the outgoing breaker is actuated usually by the closing of the incoming breaker and then the releasing of the breaker control switch by the operator. This method is sometimes called continuous, hot, or parallel transfer.

The major concern when paralleling both sources is fault current, which will be larger than that calculated for a single source. However, it is acceptable practice to design for the single-source condition if the duration of parallel operation is short. Many designs automatically trip the outgoing breaker after a short time delay or incorporate some type of indication to call attention to a prolonged parallel-sources condition. However, if the alternative source being paralleled is an onsite source, such as an engine-driven generator, short-circuit design calculations are usually based on this paralleled condition, if it exists for extended periods.

4.6.2 Automatic Transfer

An automatic transfer of the auxiliaries bus is initiated by relay operation in response to an electrical disturbance on the unit auxiliaries system (normal source). Both sources should be in synchronism. Transfer direction is from the normal to the alternative source. If transfer cannot be made due to a common disturbance on both sources (usually an undervoltage condition), the design may incorporate the capability of transferring the bus to an alternative onsite source. Due to the capacity of onsite sources, transfer of all bus loads may not be acceptable, and load shedding may be required. In addition to transferring without operator action, an automatic transfer differs from manual transfer because the auxiliaries bus is usually completely disconnected from either source at some time during the transfer.

If the power supply to the auxiliaries is interrupted for an extended period during the transfer, the generator unit could be affected due to lack of fuel, combustion air, control power, cooling, lubrication, etc. However, most generator unit auxiliaries can tolerate some interruption in power before shutdown conditions begin to occur. The duration of power interruption is dependent on the specific item of equipment. The limiting auxiliaries should be determined to ensure that there is no adverse effect on unit operation during the power interruption. In addition, if the voltage drops below 75% to 80% of the equipment rating during transfer, electrically-held motor starter contacts may open and interrupt power service to equipment. Motors essential to unit operation may have latched breakers or contactors so that they will not drop out during this transient condition. Sustained low-voltage conditions may also affect the torque-generating capability of the motors and may cause the loads to stall.

Automatic transfers can be classified as residual voltage, in-phase, and fast transfers.

4.6.2.1 Residual Voltage Transfer

During residual voltage or “delayed” transfer, the auxiliaries bus is disconnected from its normal source, and reconnection to its alternative source is intentionally delayed. This delay allows the “bus residual voltage” to decay to a safe value. The term bus residual voltage is used when referring to the effects of bus transfers on motors. Although this is discussed in more detail in Section 11., a definition of the term and a brief review of its effects on bus transfers are given here.

When an auxiliaries bus is disconnected from its power source, a residual voltage is maintained at the stator terminals of each motor due to the motor air-gap flux. The rate of decrease of this voltage on each motor is proportional to its open-circuit time constant which, depending on motor size and characteristics, could be 5 s or more. However, the adjacent motors on the bus will also have an effect on the individual rate of decrease, since high-inertia motors will act as generators driving the low-inertia motors. This will cause all motors on the bus to slow down at a somewhat constant rate and, due to the energy transfer between motors, will cause the individual residual voltages on all motors to decrease at approximately the same rate. The summation of individual motor voltages is the bus residual voltage. As the motors decelerate, the load angles of all motors will also increase, or slip, at approximately the same rate. The net effect is that all motors on the bus maintain some degree of synchronism. The load or torque angle referred to above is the phase displacement in electrical degrees between the bus voltage due to the source and the motor residual voltages. If the alternative incoming source voltage is connected to the bus when the residual voltage is out of synchronism with it, the total voltage impressed on the motors will be the resultant of these two vectors, which could exceed equipment rated voltage. Greater-than-rated voltages will cause larger-than-normal currents. Magnetic forces generated are proportional to the square of the current and may cause excessive forces and torques on the motor windings and shafts. Under certain out-of-phase conditions, transient torque values could exceed ten times the rated torque value.

To avoid this condition, many utilities use a residual voltage scheme when an automatic transfer is required. This scheme trips the normal source breaker upon a signal from an undervoltage relay, indicating low voltage on the normal source bus. The alternative source breaker closes on receipt of a signal from a residual voltage relay. This residual voltage relay actuates when residual voltage has decayed to a preset value. ANSI C50.41-1982 [B1] recommends allowing the residual voltage to decay to a value of 0.33 pu, which gives a resultant voltage not greater than 1.33 pu. Often a more conservative value of 0.25 pu is used.

When the residual voltage transfer scheme is used, the alternative source should have sufficient capability to repower the motors and bring them up to rated speed. During the reacceleration time after bus reconnection, all motors may be drawing close to locked rotor current and depressing the motor terminal voltages below motor nameplate requirements. In some cases, it may be required to load shed selected motors to ensure that total motor reacceleration requirements are not excessive. A review should be made of any equipment that may be affected by the momentary decrease in voltage during transfer (e.g., opening of starter and relay contacts).

This scheme is advantageous for undervoltage conditions on the normal bus caused by generator or turbine trips. If the undervoltage affected the alternative source, normal voltage should be restored by the time transfer is made.

4.6.2.2 In-Phase Transfer

In-phase transfers are made by using a phase angle and a sync-check relay. After the normal source breaker is tripped, the sync-check relay blocks the alternative-source breaker closure until the phase angle relay senses that the residual voltage and alternative-source voltage are either in-phase or within the limits of the out-of-phase condition allowed by the sync-check relay. Since both voltages will be in-phase, their resultant will not exceed the equipment voltage rating.

In-phase transfer has the advantages of making the transfer as soon as both voltages are in phase and not requiring a delay time for residual voltage decay. Consequently, this minimizes problems due to power interruption and decreases motor reacceleration time.

4.6.2.3 Fast Transfer

A fast transfer incorporates the use of fast-acting, stored-energy breakers (5 c breakers) that disconnect the normal source and reconnect to the alternative source before phase angle displacement of the bus and residual voltage can change appreciably. This ensures that the resultant voltage is not excessive. A fast transfer has no intentional time delay. The transfer is based on the assumption that the two sources are in synchronism.

Studies indicate that if the dead-bus time is kept to approximately 3–6 c, the angular displacement may not be excessive. (Dead-bus time is the term used to define the period when the bus is completely without power, i.e., after the normal source breaker trips and before the alternative source breaker closes.) For a 3 c delay, studies show the angular displacement to be 22° to 30°. Under this condition, the resultant voltage is less than rated motor voltage. For a 6 c delay, the displacement is 40° to 60°. Under this condition, the resultant voltage will be equal to or exceed motor rated voltage. Although the resultant voltage may exceed the rated voltage, it is not expected to exceed the recommended value of 1.33 pu. It should be noted that the above values of angular displacement are approximate. The electrical characteristics of the specific bus loads would have to be reviewed in conjunction with the relay and breaker operating time to ensure that the phase angle displacement of the bus residual voltage will not cause equipment damage. Many schemes allow a dead-bus time of up to 9 or 10 c. After this period, transfer is blocked.

Fast transfers should include provisions for ensuring that the two sources are in synchronism prior to transfer. A common method of ensuring synchronism is a sync-check relay, typically set for approximately 20°, that blocks closure of the bus breaker to the station service source if the phase angle difference between the station service and unit auxiliaries source exceeds this value.

Fast bus transfer may be one of three types: three-cycle, six-cycle, or parallel fast transfer.

These transfers are used during unit generator or turbine trips in which the initiating signal is the generator lock-out relay, or during fault conditions in which the initiating signal is the overcurrent relay.

4.6.2.3.1 Three-Cycle Transfer

Three-cycle transfers are initiated by the actuating relay, usually a generator lock-out relay, that simultaneously trips the normal source breaker and initiates a close signal to the backup source breaker (i.e., the backup breaker closes only if the backup source voltage is normal and is in synchronism with the normal source). The characteristics of breaker operation are such that, with a simultaneous signal, the tripping breaker will open before the closing breaker will close. This will ensure (if there is no misoperation) that two sources are not simultaneously connected to the bus. One advantage is that transfer time is too brief to allow residual bus voltage to slip significantly out of phase with the source voltage. This ensures continued operation of auxiliaries load with minimum disruption and permits shutdown of the generating unit in a more orderly manner. A disadvantage is that the operating time is so fast that should a fault occur on either source during transfer or should a fault be the cause of the transfer, and should the normal tripping source breaker remain closed to the bus or become stuck, the faulted condition may be seen simultaneously by the normal and alternative sources. This will result in an additional short-circuit contribution from the alternative source, which could overstress equipment.

4.6.2.3.2 Six-Cycle Transfer

Six-cycle transfers are initiated by the actuating relay that trips the normal source breaker. Closing of the alternative source breaker is initiated by an auxiliary “b” contact on the normal source breaker after it is open. In practice, an early “b” auxiliary contact that is faster-acting than the normal “b” contact is often used. An advantage of this scheme is that the alternative source breaker will not close until the normal source breaker is open. This assures that the two sources will not be simultaneously closed into a fault. A disadvantage is that the transfer time could exceed the safe “dead-bus” period of approximately 9 to 10 c. The delay times included in the relay protection design should be reviewed to ensure their adequacy for the transfer scheme selected.

4.6.2.3.3 Parallel Fast Transfer

Parallel fast transfers are similar to the manual transfers addressed in 4.6.1. The transfer is automatically initiated by the generator lock-out relay that closes the alternative source breaker, momentarily paralleling the alternative and normal source. An auxiliary “a” contact on this closed breaker will then trip the normal source breaker. An advantage is that there is no dead-bus time. A disadvantage is that, should a fault occur, the two sources may be simultaneously closed into it.

4.6.3 Unit Conditions During Startup/Shutdown Transfers

A detailed treatment of unit operating and loading conditions during startup is beyond the scope of this guide. However, some general observations are made to illustrate the effects on the station service system.

The auxiliaries bus (or buses) is transferred from the station service system to the unit auxiliaries system when the generator is up to rated speed and voltage, in synchronism with the power system, and when the steam/fluid conditions of the unit (e.g., pressure, temperature, flow, etc.) are within the required range. It is common practice to partially load the unit before transfer. The sequence of startup procedures to place the unit in this condition depends on individual unit characteristics. Prior to startup, some plant auxiliaries are functioning with power supplied from the station service system. They are supplied from energized distribution buses and include instrumentation and control equipment, lighting, HVAC, and communications. After these auxiliary systems are operational, the condenser cooling or circulating water system is started, followed by service water, compressed air, condensate and feed water, and, finally, the combustion air and fuel systems. Steam is then generated in the boiler, and the turbine-generator is brought to rated speed and synchronized to the power system. For large units, transfer to the normal source would occur when the unit is able to accept approximately 15% of its nameplate load rating. Smaller units would transfer in the range of 20% to 30% of rating. These percentages are general guidelines only and vary with the individual unit. As an example, large, once-through critical units may not be stable below 30% of nameplate rating, and the transfer time would be adjusted accordingly. It should be noted that auxiliaries system power required at the time of transfer is not directly proportional to unit generator output (i.e., when the unit output is 15%, the auxiliaries system power required to maintain this output is much greater than 15%, the auxiliaries system power required to maintain this output is much greater than 15% of the total auxiliaries system power requirement during normal operation). One reason for this is that many auxiliary motors will be in operation during this period, but they may be lightly loaded. In this operating mode, their power factor and efficiency will be low. Therefore, the station service system should be sized for the maximum startup/shutdown design basis requirement.

It should be emphasized that the above observations are general. The exact time of transfer is determined by both station operating procedures and the station operator, based on individual unit conditions and experience, as is the exact sequence of loading and the load requirements of the unit.

Shutdown transfer to the alternative source will be similar in the reverse direction.

4.7 Protective Systems

Protective systems function to ensure personnel safety and to protect against equipment damage. During an unscheduled or emergency shutdown caused by a unit trip, a fault condition, or the loss of both the normal and startup/shutdown sources, the requirement of continuous power is even greater for protective systems. Accordingly, an alternative or standby power supply is often provided from an onsite source that functions as a backup to the normal and startup/shutdown sources of supply to these systems. Although an exact listing of protective systems requiring this onsite source is dependent on the particular unit generator, the following are considered to be protective systems that are provided usually with at least one onsite source.

4.7.1 Turbine-Generator Auxiliaries Systems

Due to their cost and potential for damage to plant and personnel the following turbine-generator auxiliaries systems are supplied usually from an onsite source.

4.7.1.1 Lubrication System

Large turbine-generator bearings require continuous forced lubrication and water cooling during both operation and coastdown, and may be damaged if this is interrupted while the shaft is still rotating. In addition, bearing damage could decrease the clearances between the rotating and stationary elements and result in further damage. After a unit is shut down, it must continue to be rotated to assure uniform cooling in order to prevent thermal bowing (eccentricity) of the rotating element.

For a typical unit, lubrication motors consist of the following:

- 1) Shaft-driven main bearing oil pump (MBOP)
- 2) AC motor-driven turbine bearing oil pump (TBOP)
- 3) DC emergency bearing oil pump(s) (EBOP)

The shaft-driven main bearing oil pump is mounted on the turbine shaft and delivers lubricating oil during normal operation. During startup and shutdown, the ac oil pump motors supply oil when the main shaft-driven pump is not up to pressure. These ac motors are backed up by the dc emergency bearing oil pump, which is fed from a station battery and started automatically on low oil pressure. A second backup dc pump is sometimes provided. Lubrication motors may also include the bearing lift pump motors (some large units cannot be placed on turning gear without the lift pumps running) and the turning gear oil pump motor.

4.7.1.2 Hydrogen Seal System

Hydrogen is often used as a coolant for large generators because its heat transfer and electrical properties are superior to nonexplosive gases. High-purity hydrogen will not support combustion. However, when mixed with air to a level of 95% purity, it is considered explosive. Therefore, a sealing system must be provided to prevent the hydrogen gas from escaping the generator casing. This is done by maintaining pressure on an oil seal around the generator shaft. As long as the oil pressure is greater than the hydrogen gas pressure, a seal will be formed confining the gas inside the generator and preventing leakage to areas outside the casing.

For a typical unit, the seal oil motors would consist of the following:

- 1) AC main seal oil pump (MSOP)
- 2) DC emergency seal oil pump (ESOP)
- 3) AC motor-driven vacuum pump

The main seal oil pump is used normally and is backed up by the dc emergency seal oil pump, which is fed from the station battery. These pumps circulate oil through the seals while the vacuum pump removes the hydrogen from the oil

in the hydrogen drain tanks. Some vendors will furnish two main seal oil pumps instead of one. These two pumps, one for each side of the seal, are called the air-side and hydrogen-side seal oil pumps.

4.7.2 Burner Management Systems

Fossil-fueled steam generators must be designed so that the fuel supply will be interrupted if there is a loss of water supply. Otherwise, fired metal parts under steam pressure could become overheated, due to lack of cooling, causing failure or explosion. In addition, loss of ignition at the burners will result in unignited fuel being injected into the steam generator furnace, which could result in an explosion if the fuel were ignited either from hot metal parts from or accidental initiation of the burner system. To ensure that the fuel supply is interrupted, automatic controls (burner management systems) are provided that continuously monitor burner ignition, fuel, air, and water supply and that interrupt power to the supply valves when a hazardous condition is detected. To provide assurance that the system will always fail-safe, the control valves, dampers, and feeder breakers should be energized continuously in the operating position or should have the required control circuitry so that they will automatically close and shut down the unit upon loss of control power. Therefore, they require a continuous source of power.

4.7.3 Electrical Protection Systems

A source of electrical power for closing and tripping power supply breakers and for relays is provided usually from an onsite source, because lack of control power for these devices could result in damaging electrical conditions such as short circuits, overcurrents, and undervoltages remaining on the electrical system. In addition, many circuit breakers are latched mechanically so that they will remain closed for transient fault conditions. These breakers require an onsite source for tripping when all power is lost. These devices can be obtained for operation on either ac or dc power. Control power for switchgear breakers in generating stations is normally from the station battery.

4.7.4 Instrumentation and Control Systems

Due to the increasing use and reliance on instrumentation and control devices in generating plants, most devices that control or monitor protective systems will be connected to an onsite source of power. Included in this category would be plant computers or other devices that cannot tolerate an interruption in power and that must function to assure that data is collected during fault and transient conditions.

4.7.5 Miscellaneous Systems

Miscellaneous systems requiring an onsite source are those systems not usually required for operation of the auxiliaries, but which may be required when normal power is lost, such as fire protection, elevators, battery chargers, HVAC, and emergency lighting systems.

4.8 DC, DC/AC, and AC/DC Power Sources

To ensure a reliable source of dc power to dc protective equipment and systems, an onsite dc source is normally provided in the generating station. DC loads are supplied continuously from this onsite source and, with suitable isolation and suppression devices, are essentially independent of the station service and unit auxiliaries system. These sources are used where power requirements are relatively small and of short duration. The supply is generally considered to be uninterruptible.

Onsite dc power sources usually consist of two main components: the storage battery and its associated battery charger. This combination provides the high reliability that is attributed to dc power supplies.

Also included is an item of equipment generally associated with the battery and charger, the inverter, which is powered from the dc source but supplies ac power. These three components, when combined, provide an un-interruptible power system (UPS) that furnishes a continuous, highly-reliable source of ac supply.

In this section, a brief description of motor-generator (M-G) sets is also included since these are used, in special circumstances, as a UPS.

4.8.1 Storage Battery

The battery charger normally provides power to protective equipment and systems that cannot tolerate a power interruption and also normally provides a trickle charge to the battery. Therefore, the battery is normally maintained at full charge and is available continuously to provide power to the system.

Battery use is standard for most generating units to supply all dc powered equipment, including motors, instrumentation and control (including circuit breaker controls), alarms, emergency lighting, and UPS. The reliability of service may be reduced by the aging characteristics of the batteries. However, when properly tested and maintained, and when used in conjunction with a battery charger, the battery is regarded as the most reliable power source in the generating station. In addition, when an inverter is added, an extremely reliable source of ac power is also provided.

4.8.1.1 Battery Types and Construction

The most common type of battery used in generating stations is the lead-acid type. Two different classes of the lead-acid type of station battery are the lead-calcium and lead-antimony. The term “lead” defines the major component of the plate material, and the terms “calcium” and “antimony” define the additives used with the lead that give the specific type of battery its unique characteristics. For example, the lead-calcium type generally has a longer life than lead-antimony, but it costs more. These additives may be included either in the plate material or in the surrounding grid that supports the plate material.

Each set of plates (one set positive and one set negative), with its supporting grid and connectors, is called a cell. The composition and configuration of the plate and grid material determine one of the two basic characteristics of the battery, the voltage per cell.

4.8.1.2 Voltage Rating

The basic battery unit is the cell. One of the two primary electrical characteristics of each battery cell is its volts per cell. The nominal voltage on a lead-acid cell is approximately 2.05 V per cell. Connection of these cells in series furnishes the standard battery voltages required for dc equipment operation. For a 60-cell battery with a nominal rating of 2.05 V per cell, the nominal output voltage would be 125 V dc.

The dc equipment powered by the battery must be specified to operate within the design battery voltage range, which is typically 2.33 to 1.75 V per cell. For a 60-cell battery, this corresponds to a battery terminal voltage of 140 V to 105 V dc, respectively. This minimum value of 105 V dc is the battery terminal voltage at the end of the discharge cycle and does not include the voltage drop in the cable connecting the load to the battery. Since batteries are generally located in one central location, loads that are relatively distant from the battery may have appreciable cable resistance voltage drop, which may require oversized feeder cables. A typical design may specify dc equipment to be suitable for operation at 101 V dc. This would allow a feeder voltage drop of 4 V. In some systems, a lower limit of 90 V dc may be selected, but only equipment rated at this lower voltage should be used. For example, 90 V dc would be an acceptable control voltage for most breakers but would not be satisfactory for dc motors. Prolonged operation of equipment at too high a voltage may also be damaging. This problem is due primarily to specifying too narrow an equipment voltage range or operating the battery charger at too high a voltage, resulting in overheating of the equipment and degradation of its insulation.

In general, 60-cell batteries (125 V dc nominal) are used in most stations. In some stations, where large dc motors are required, or where the feeder voltage drop is excessive, 120-cell batteries (250 V dc nominal) also may be used. Large dc motors are used often in the turbine-generator auxiliaries system (see 4.7.1). In situations in which both ratings of battery are used in a station, the 250 V dc will usually supply only large loads, and the 125 V dc will supply small motor loads and instrumentation and controls. Less frequently, 48 V or 24 V dc systems are used.

4.8.1.3 Ampere-Hour Rating

The second primary electrical characteristic of the battery is its ampere-hour (Ah) capacity, which is a measure of its ability to supply specified loads for a certain time period (discharge period). To be acceptable for critical applications, the battery must be capable of supplying the required amperes at the minimum specified voltage at all times during its discharge period. A standard procedure for calculating this capability is provided in IEEE Std 485-1983 [B5]. Using this procedure, the required dc loads are tabulated with respect to magnitude and duration. This tabulation establishes a load vs. time profile that is called a “duty cycle.” Using this duty cycle and using manufacturer’s curves that show the Ah capacity at a specified discharge rate, the required battery capacity may be calculated. The capacity requirements may be reduced if loads are connected to the battery in a certain sequence, for example, if controls are provided to assure that large dc motors are not started simultaneously. Typical station batteries range from 200 to 4000 Ah with typical discharge rates of either 2, 3, or 8 h. The storage capacity of the battery is dependent on the type, construction, operating temperature, rate of discharge, and age of the battery. Although most batteries will show increased capacity for a short time after initial use, all batteries will have decreased capacity with increasing age.

The capacity of the battery, since it is an electrochemical device, is affected directly by its temperature. Battery capacity is usually given assuming a battery temperature of 25 °C (77 °F). For higher temperatures, capacity may be increased; for lower temperatures, capacity will be reduced. At 0 °C (32 °F), the capacity may be reduced to approximately 70% of its normal rating at 25 °C (77 °F). However, higher ambient temperatures decrease battery life, even though capacity may be increased. For this reason, rooms dedicated to the station batteries may require special consideration to maintain proper temperatures.

4.8.1.4 Testing and Maintenance

Periodic battery testing and maintenance is usually done to ensure acceptable capacity and voltage and to identify potential problems. IEEE Std 450-1987 [B3] provides procedures and recommends replacement criteria. It should be noted that these criteria should be applied to allow sufficient time for battery replacement, since there must be reserve capacity at the time of the periodic test to ensure that the battery will continue to supply its design requirements until it can be replaced.

4.8.2 Battery Charger

The battery charger functions in conjunction with the battery. It is the combination of these components that provides the high degree of reliability exhibited by dc onsite sources. The modern static battery charger incorporates solid-state components and functions as a rectifier. Its ac input power is rectified into dc output power.

The charger is operated usually in parallel with the battery. During normal operation, the charger will supply the dc loads and maintain the battery in a properly charged condition. During abnormal or emergency conditions in which the dc load is high, the battery will assist in powering loads that are beyond the capability of the charger. It should be noted that when the charger is used to provide a direct supply for dc loads, this requirement should be specified in order to incorporate the necessary filtering. Chargers that do not power dc loads do not require additional filtering. This would be the case in which a charger was used only to charge the battery or supply an inverter. To ensure that power for the dc loads will be adequate, the charger is sized to supply the normal dc load while simultaneously recharging the discharged battery in a specified time period. In addition to powering normal dc load, the charger must “charge” or furnish charging current to the battery to ensure the battery is maintained at full charge or capacity. Battery charging is done by operating the charger in one of two modes: the “floating” mode or the “equalizing” mode. The floating mode is used for normal day-to-day charging and maintains a voltage on the battery slightly higher than the battery open-circuit voltage. The approximate float voltages for lead-acid type batteries are 2.15 to 2.20 V per cell for antimony and 2.17 to 2.25 V per cell for calcium types.

The equalizing mode maintains a higher voltage on the battery than the float voltage and is used to bring all cells up to the same charge. This is done because, at floating voltage, charging current is so small that voltage differences in the various cells may exist. The equalizing charge will be done usually at some periodic interval, usually monthly. The floating charge is usually applied continuously. The equalizing charge also will be given usually after the battery is