CHAPTER 11

Electrical Systems

Prepared by
Dr. Jin Jiang[1]
Department of Electrical & Computer Engineering
Western University

Summary

This chapter covers grid requirements, station power systems, and major electrical components in CANDU nuclear power plants (NPP). Grid requirements at an NPP location are discussed in terms of reliability and availability of off-site power, the need for a secure electricity supply for the electrical generation process, and the role of electricity in ensuring the safety of CANDU nuclear power plants. The chapter also describes the operating principles of the major pieces of electrical equipment found in a CANDU plant.

The chapter is divided into four parts. In the first part, general and nuclear safety-based principles and practices for the design of electrical systems in CANDU 6 plants are listed.

In the second part, the main electrical connection to the power grid is explained. The concepts of switchyard, protection schemes, grid connection, and synchronization are also addressed from a CANDU NPP point of view. The chapter considers situations involving electric power production during normal operation, as well as power consumption for maintaining plant safety during shutdowns. The relationship between internal station power, generated power, and grid power is clarified in light of reactor safety.

The third part discusses the internal plant electrical system. The section offers a detailed classification of power sources by their reliability levels and explains the interrelationships among them. The section also provides a justification for the classification of these power sources and introduces the concepts of DC power sources, standby power supplies, and emergency power systems.

The final section briefly introduces the major electrical systems and devices in a CANDU plant, including the generator, transformers, voltage/current transducers, and circuit breakers. The section first explains the operating principles of these systems and devices and then provides their specific ratings and designs in a CANDU plant.

To facilitate learning, a list of exercises has been compiled at the end of the chapter. The reader

1 with contributions of Sections 1.1, 1.2, 3.3, 3.7, 3.8, and 3.9 from Mr. Alek Josefowicz, P.Eng., CANDU Energy (Retired)

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

should attempt to answer these questions to gain further understanding of the materials presented. Additional information on electrical systems in nuclear power plants can also be obtained through the list of key references provided at the end of the chapter.

It is important to note that electrical systems may vary slightly in different CANDU plants. For example, some diagrams may show elements of shared systems, the CANDU 6, as a single unit design where the design principles exclude sharing except for the switchyard. The main goal of this chapter is to provide a basic knowledge of electrical systems in a CANDU plant, rather than to examine details of a specific plant.

Learning outcomes

- The goal of this chapter is to provide students with a clear understanding of the importance of the availability of electrical power for maintaining the safety of a nuclear power plant under conditions different from the normal mode of operation, but which are, however, within the conditions evaluated in the safety analysis report.

- Students should be able to explain why grid power is as important to the safety of an NPP as the power output from the NPP is to the grid.

- Students should be able to identify any deficiency in the reliability of the power grid at the power station location.

- Students should be able to read the station power distribution diagram by identifying different classes of power sources, i.e., Class I through Class IV. They should also be able to match the names of the safety-related systems with the corresponding power classes.

- Students should be able to describe the relationships among the different classes of power sources.

- Students should be able to explain the functionalities of both standby generators and the emergency power system.

- Students should be able to list the major systems involved in power generation and transmission.

- Students should be able to explain the principles of energy conversion from mechanical energy to electrical energy through synchronous generators.

- Students should be able to describe the functionality and working principles of the excitation and cooling systems of the synchronous generators.

- Students should be able to describe the working principles of transformers and voltage/current transducers, as well as to identify where in the plant they are used.

- Students should be able to identify and describe the different types of circuit breakers and disconnect switches.

- Finally, students should be able to explain how the generated electricity is delivered to millions of customers.

Table of Contents

List of Figures

List of Tables

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

1 Introduction

1.1 General

Even though the sole objective of a nuclear power plant is to generate electricity, it takes electricity to run the entire plant. The electrical power system in a nuclear power plant is the subject of this chapter. The electrical systems are designed not only for normal plant operation, but also for conditions other than normal operation, so that plant safety can be maintained by ensuring continuity of electrical power supplies regardless of transient disturbances or faults during operation and post-shutdown. The power for an NPP comes from diverse and reliable power sources that are physically and electrically isolated, so that any single failure will affect only one source of supply and will not propagate to alternative sources.

Even after the reactor has been shut down, a significant amount of heat is still being produced by the decay of fission products (decay heat). The amount of decay heat is sufficient to cause fuel damage if not removed effectively. Therefore, systems must be designed and installed in the plant to remove decay heat from the core, even in a plant shutdown condition and in the absence of off-site power sources.

The electrical power distribution system (EDS) is a complete load group distribution system with two independent off-site power sources, the main turbine generator, and on-site standby power sources (standby and EPS diesel generators and, in some cases, a station blackout generator).

1.2 Nuclear Safety-Based Design Principles and Practices for a CANDU EDS

- The EDS needs to be designed in accordance with its safety functional requirements as defined in the safety analysis, including independent and diverse provisions aligned with independent safety functions and including provision to supply electrical power to secure plant safety during both normal operation and accident conditions without losing all on-site power.

- The divisions of the power supply systems should be physically and electrically separated from each other, thus ensuring independence among the divisions as much as possible.

- The Group 1 and Group 2 power supply systems should be physically and electrically separated from each other as much as practically possible.

- The design of the EDS and associated support systems, including I&C, HVAC, and cooling systems, should follow the classification, independence, redundancy, and diversity requirements placed on Structures, Systems, and Components (SSCs).

- The EDS should be designed for a wide range of electrical transients which can be assumed to occur during plant operation and for the assumed environmental conditions.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

- The EDS should be designed for or protected from effects of both internal and external hazards, such as short circuits or loss of the power grid.

The EDS uses commercially available conventional hardware with provisions as dictated by the need for seismic qualification (SQ), qualification for operation in a harsh environment (EQ), and radiation hardening. Electrical containment penetrations (ECP) form part of containment.

2 Electrical Power Grids and their Connection with an NPP

2.1 A Holistic View of Electrical Systems between an NPP Station and the Grid

Even though each specific plant may have its own unique characteristics, a typical set of electrical connections between a CANDU station and the power grid is illustrated in Fig. 1.

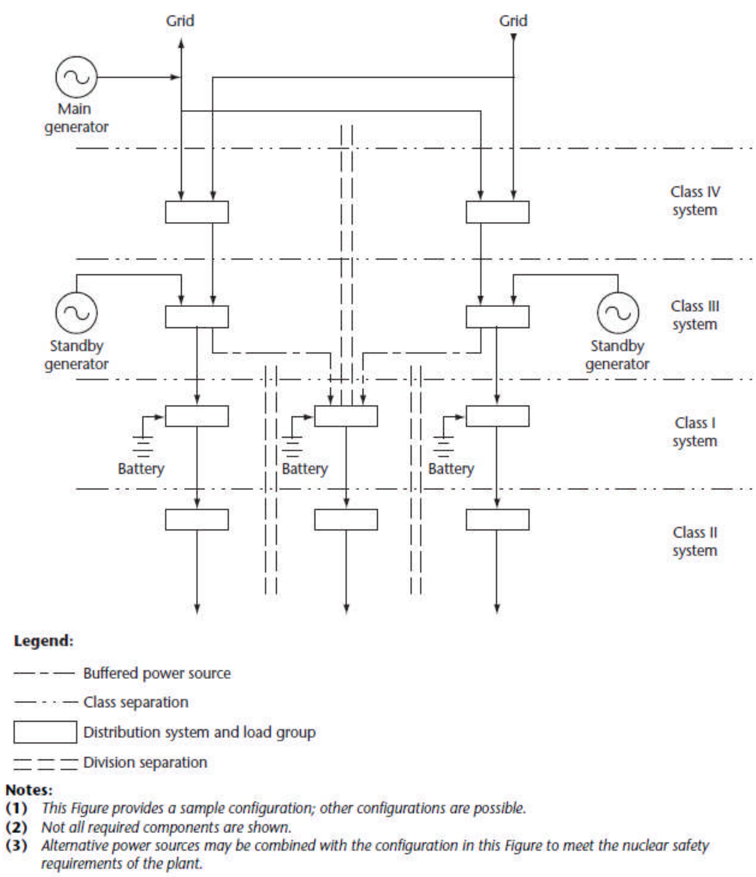


Fig. 1 - Relationships between the station power and the power grid [1].

A station can have either a single reactor unit or multiple reactors. During normal operation, the generated power is fed to the power grid through *main output transformers* (MOTs). In addition, a portion of the generated power is also fed back to the units to support electricity

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

production through *unit service transformers* (USTs). Furthermore, it is good practice to cross-link multiple units at the switchyard to increase self-reliance within the station, particularly in situations where one shutdown unit may need to draw power from other units within the station to remove decay heat from the reactor, to maintain essential operating services, or to re-start the reactor as long as it has not been poisoned out by xenon.

When the power from the station units is no longer sufficient or available to meet internal demand, the station can draw additional power from the grid through *station service transformers* (SSTs). This is also the case during a start-up process.

It is assumed that the power grid is stable and that there are other power sources connected to the grid, which are available when needed to provide power to the nuclear station site itself. The power flow on the grid can be effectively controlled through grid interconnection and management systems. The NPP may contribute to voltage and power control in the grid. However, most existing CANDU power plants operate in a constant-power output mode to support the base load supplied by the grid.

2.2 Unique Grid Power Requirements for NPP Safety

The main objective of a nuclear power plant (NPP) is to produce electricity to support industrial, commercial, and residential loads. Electricity is therefore the final product for most NPPs. However, it is important to realize that about 8% of the electricity produced by the plant is consumed internally to support power production. This is true for most power plants, such as coal or gas, although their internal consumption may be significantly lower (<4%). NPPs, however, have unique requirements for electric power availability. It is particularly important to have a secure electrical supply when an NPP is in a shutdown state and is not producing any electricity of its own. Even when the fission process in a nuclear reactor stops, a significant amount of decay heat continues to be generated from the fission products. The amount of heat is typically so large that continued cooling is absolutely necessary to protect the fuel sheath from melting. Pumping cooling fluid through the core removes this excess heat, but requires an external electrical power source. Hence, the availability of electrical power (from other units or from the grid) is crucial for the safety of CANDU and other nuclear power plants both under normal operations and in a shutdown state. This includes situations where thermosiphoning is used. Electrical power is required in this case to maintain water in the steam generators, although pumping of primary coolant is not needed.

This unique requirement for electricity requires consideration of different scenarios at the design stage of NPP electrical systems. In CANDU power plant design, the NPP site must be chosen so that the power grid at the site has multiple feeders from different and independent (often geographically separate) sources, as shown in Fig. 1. This requirement ensures that off-site electrical power sources are available to the station for removing decay heat when the reactor is shut down and is no longer producing electrical power of its own. In addition to Canadian standards [1,2] for a CANDU NPP, the International Atomic Energy Agency has also issued guidelines for selecting suitable sites for other types of NPPs based on the reliability and

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

availability of off-site power [3,4], as has also The Institute of Electrical and Electronics Engineers (IEEE) [5]. As explained in Chapter 13, the availability of off-site electrical power will affect NPP safety analysis.

As a part of the site selection process, the reliability of the grid must be assessed when some of its generating capabilities are assumed to be no longer available. This is often referred to as the (*N*-1) problem [6], where *N* is the number of available units. A desirable site for an NPP is one where power delivery to the NPP site is still guaranteed when only (*N*-1) or (*N*-2) suppliers are available.

The main cause of the 2011 disaster at Japan's Fukushima Daiichi nuclear power plant was a lack of off-site power due to the earthquake and inadequate protection of on-site standby power systems against a tsunami. All the plant's on-site diesel generators operated until they were damaged by the water brought in by the earthquake-induced tsunami. Hence, the leading cause of the disaster was the lack of power after the successful shutdown and an initial period of reactor cooling.

Together with other facilities in a CANDU plant, the electrical systems must also meet the seismic design requirements and qualification processes as outlined in [7] in Canada.

2.3 Switchyard between the Grid and a CANDU NPP Station

Note that even though a single line is used to show the flow of power in Fig. 1, all lines carry three-phase power (except DC power lines). All transformers, circuit breakers, and transmission lines in an AC power grid are three-phase devices. When delivering the generated power to the grid, the station power must be synchronized with the grid, including the phase sequence, voltage levels, and AC power frequency. Voltage and current transducers are used for monitoring and control, and several high-voltage, high-current circuit breakers are placed between the MOT and the grid connection points.

The switchyard contains numerous control and protection devices to ensure that any faults on the grid side will not induce major disturbances to the station, and vice versa. There are also various interlocks to prevent the incorrect operation of power devices, as well as lightning arresters, grounding protection systems, and switchyard control systems.

2.4 Summary

Even though the main function of an NPP is to produce electricity to supply power to the grid, unlike other types of thermal power generation systems, an NPP requires an external power source with on-site backups to remove decay heat from the reactor when the plant is in shutdown mode and is not producing its own electricity. Therefore, significant design considerations have been formulated for the electrical systems within a nuclear power plant. Furthermore, the availability of off-site power also plays a crucial role in nuclear power plant

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

safety and is one of the most important considerations in the site selection process when constructing a new NPP.

3 Electrical Systems Internal to a CANDU Plant

3.1 Sources of Electrical Power for CANDU NPP Station Use

Almost all systems within an NPP rely on electrical power to operate. A “defence-in-depth” strategy for electrical power supplies is to rely on diverse, multiple, and independent sources. These sources for a CANDU unit are: (1) power generated from the unit itself; (2) power generated from other units within the same station; (3) off-site power obtained from the grid; (4) the emergency power supply; (5) the standby power supply; and (6) batteries. The power sources in a CANDU NPP consist of both AC (alternating current) and DC (direct current) power. “Defence-in-depth” as applicable to the electrical systems can be stated as follows:

- 1st line – normal operation (grid + main generator)
- 2nd line – mitigation (standby generators + batteries)
- 3rd line – station blackout (batteries + designated alternative source(s))
- 4th line – severe accident management (additional, diverse, alternative sources).

These sources are arranged in such a way that they supply power to station systems during normal operation, as well as during emergency conditions to maintain NPP safety. The equipment in the station is also graded according to its importance to safety. In an event that electrical generation is lost, limited alternative power sources will be used first and foremost to keep the essential safety-related systems operating.

A CANDU plant contains several buses at different voltage levels. The selected voltage levels might be different in different plants to meet certain country-specific requirements. One example is shown in Fig. 2, where the output voltage level of the generator is at 22 kV, and the voltages at the unit service transformer (UST) and the station service transformer (SST) are at 11.6 kV and 4.16 kV as secondary voltages. However, in other designs, these voltages could be 13.8 kV and 4.16 kV. Also shown in Fig. 2 are two connections to off-site power at the NPP site, one at 500 kV and the other at 220 kV.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

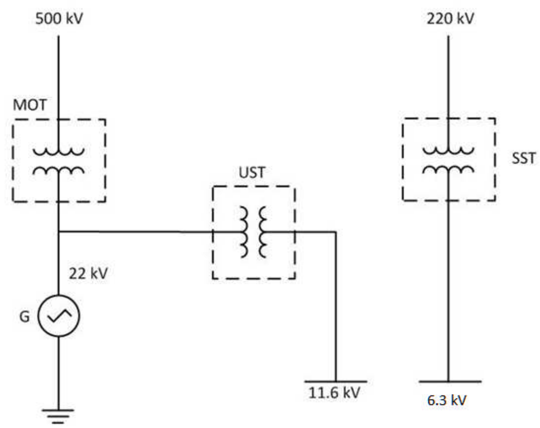


Fig. 2 - Voltage levels within a CANDU plant.

Several other low-voltage buses exist throughout the plant and will be discussed further in the next section.

3.2 Class Definition of Power Sources

Electrical power sources in a CANDU plant can be divided into four levels, according to the allowed duration of voltage interruption that can be tolerated by the loads they supply. Class I power supplies loads that cannot be interrupted. Loads on Class II power can tolerate ~4 millisecond interruptions. Loads on Class III can withstand power interruptions of up to 5 minutes, whereas Class IV loads can tolerate loss of power indefinitely. The most critical and safety-related control and protection systems are powered from Class I and II sources. Different classes of power supplies provide power to different systems, depending on the amount of power the systems require and their relative importance to safety.

Typically, the cost per kW will decrease as the power supplies move from Class I through to Class IV. The power capacities also increase from Class I to Class IV. The allowable interruption times and capacities of the various power sources are summarized in Fig. 3.

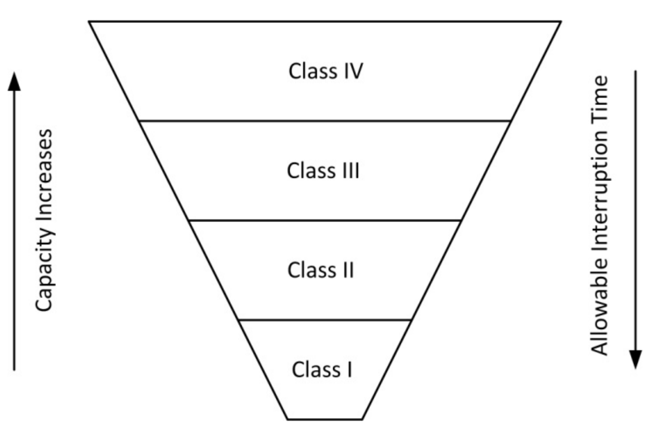


Fig. 3 - Allowable interruption time vs. capacity of the different power classes.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

To determine which class of power should be used to supply a specific system, the safety functionalities of the system must be examined, as well as the economic impact if that supply were unavailable. General criteria for matching the class of power supply to the load that it supports are summarized in Table 1. They are expressed in terms of the longest power interruptions that will not affect the safety of either the NPP or its personnel.

Table 1 - Classification of power sources

Class of power	System load characteristics
Class I	Power can never be interrupted under postulated conditions
Class II	Power can be interrupted up to 4 milliseconds
Class III	Power can be interrupted up to 5 minutes
Class IV	Power can be interrupted indefinitely

Different stations may have slight variations in electrical power system configurations. An illustrative diagram showing interconnections in the electrical power system for the different classes of power sources in a CANDU station is presented in Fig. 4.

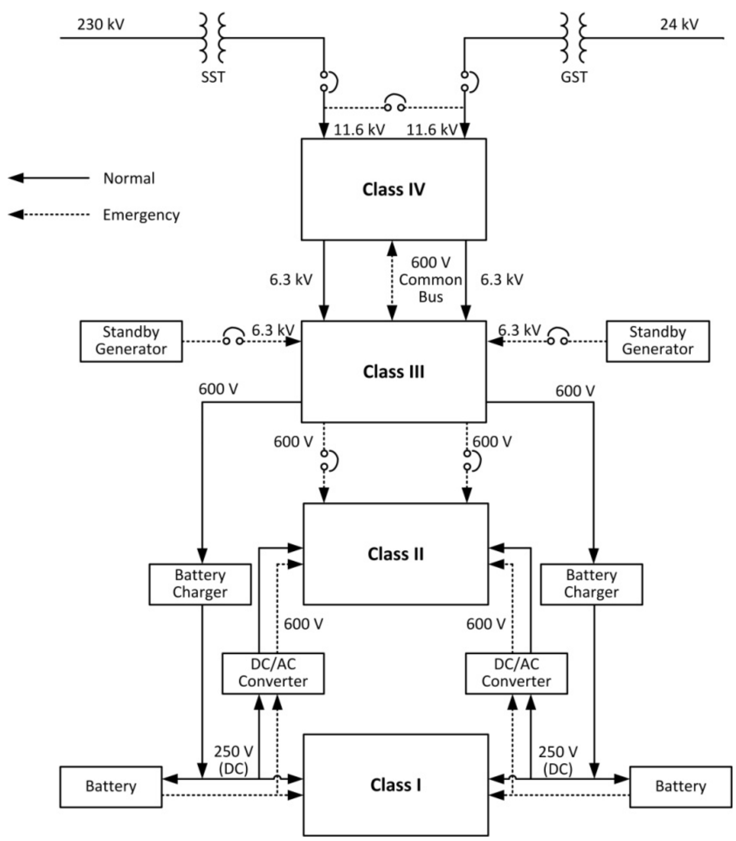


Fig. 4 - Interconnections of different classes of power supplies.

To increase reliability further, Class II, III, and IV power are distributed through two separate

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

power divisions. If a failure occurs on one division, the equipment connected to the other bus will still be available. In CANDU plants, these two divisions are typically denoted as “Bus A” and “Bus B” or as “Odd Bus” and “Even Bus”. During design, loads are distributed evenly between these two divisions.

An example of such a split-bus connection is shown in Fig. 5. A symbol with two circles and an arch over them represents a circuit breaker. Circuit breakers are used to connect or disconnect the systems (denoted as loads) and to protect them whenever a fault occurs. The connection between the Odd and Even buses on the diagram represents two circuit breakers, one on each bus. To accomplish the connection, both breakers must be manually commanded to close.

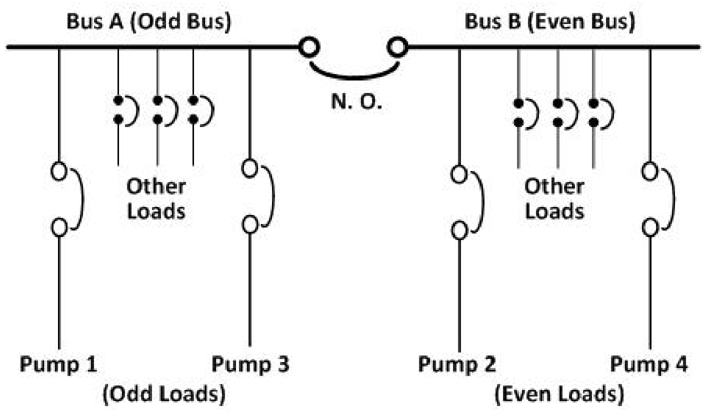


Fig. 5 - Dual-bus configuration for power distribution systems.

3.3 Channelization

Important functions use three instrument channels to provide immunity against single instrument faults. A control channel consists of interconnected hardware and software components that process one of the duplicated or triplicated signals associated with a single parameter. A control channel may include sensors, data acquisition, signal conditioning, data transmission, bypasses, and logic circuits. This defines a subset of instrumentation that can be unambiguously tested or analyzed from end to end. For safety and high-reliability applications, I&C system design uses three instrumentation channels with a two-out-of-three voting strategy (i.e., two of the three channels must be outside the acceptable limits to trip or actuate the system).

To perform on-line tests in such a design, the operator will place the tested channel in a trip state, resulting in the actuation logic performing a one-out-of-two test on the remaining channels. Process and safety systems channels are assigned as shown in Table 2.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

Table 2 – Channelization.

System(s)	Safety Group	Odd (**A**) Associated Channels	Third (**B**) Associated Channels	Even (**C**) Associated Channels
RRS and Process	1*	A	B	C
SDS1	1	D	E	F
ECC (NSQ)	1	K	L	M
SDS2	2	G	H	J
ECC (SQ portion)	2	KK	LL	MM
Containment	2	N	P	Q

- The channel association also applies to separation of power supplies and cabling. During normal operation, channels A, B, and C of the UPS supply all their associated channels.
- Group 1 is primarily for power production, and Group 2 is only for safety systems. Physical separation is required between the two groups.
- Group 2 systems can also be powered from the EPS. Functional and physical separation is maintained even though in this situation, only one EPS generator supplies one bus from which the three channelized power sources are derived.
- '1*' denotes non-safety, however, it is associated with Group 1, and
- NSQ means "not seismically qualified", and SQ means "seismically qualified".

3.4 Electrical Power Sources under Different Classes

3.4.1 Class I

Class I power is used to supply loads that cannot be interrupted. It is a DC power source with three independent distribution channels, each backed with battery banks to provide uninterrupted power to critical loads. To maintain adequate charge on the batteries, each bus in Class I is connected to power rectifiers, which convert AC power from Class III power sources to DC to charge the batteries, as shown in Fig. 4. During normal operation, power from the rectifiers is used to support the load on this bus while charging the batteries at the same time. Hence, the batteries always remain fully charged when power is available. DC/AC inverters are also used to convert DC power from Class I to Class II. In the event of a loss of Class III power, batteries provide a seamless transfer to support the loads without any interruption. Note that the batteries are capable of supplying the load on the DC buses for only about 60 minutes, depending on the particular plant design. This is a very critical time window because all Class I and II power would be lost if Class III power could not be restored within the interval provided by the batteries.

The loads supported by the Class I power source are very sensitive and are critical to NPP safety and operation. A partial list of system equipment powered from Class I is provided in Table 3.

Table 3 - Equipment supported by Class I power supplies.

Class II inverters
DC seal oil pumps for generator
DC lube oil pump for turbine generator bearings
Turbine trip circuits
Turbine turning gear
DC stator cooling pumps
Control and protection systems for station electrical distribution systems
Logic, control, command circuits, and operator interfaces for process and safety systems (48 VDC)

The capacity of the Class I power source is based on the connected load. CANDU plants use several different voltage levels for this DC power supply, including 48V, 220V/250V, and 400V, all to meet the needs of the NPP's various systems. Note that loss of Class I power is one of the conditions that trigger the shutdown systems.

To prevent service interruption caused by a "single line-to-ground" fault, the 48V DC and 250V DC systems are ungrounded. Ground fault detectors, which produce an alarm whenever a ground fault occurs, are provided for each bus.

3.4.2 Class II

Class II power sources are critical to reactor operation. If Class II power is lost, the reactor will be shut down immediately. Under normal operation, Class II power is obtained from Class I sources through power inverters to convert DC power to AC power, as can be seen in Fig. 4. If for any reason the inverters cannot supply a given bus, the Class III power source will be used to support Class II power distribution.

The Class II power source supports those devices and systems that can tolerate power interruptions on the order of milliseconds. Some typical systems supported by Class II power source are listed in Table 4.

Table 4 - Equipment supported by Class II power supplies.

Digital control computers
Reactor regulation instrumentation
Electrically operated process valves (600 V power distribution)
Auxiliary oil pumps on the turbine and generator (600 V power distribution)
Emergency lighting (600 V power distribution)

Three independent channels of single-phase inverters ensure complete supply independence to the triplicated instrumentation and I&C. Class II power sources are relatively low-capacity, have two voltage levels: 120V and 600V, and are available only in AC form.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

3.4.3 Class III

Class III power supports large process loads that are unsuitable for Class II power supplies. They are used mainly to maintain fuel cooling when the reactor is in a shutdown state and Class IV power is unavailable. It is important to note that the duration of the loss of Class III power consists of only the time required to start up a standby generator and re-load the Class III power system, which is normally about five minutes.

Class III power is taken from Class IV power. In the event of total loss of auxiliary power from off-site sources, the auxiliary power required for safe shutdown will be supplied from physically and electrically independent diesel generators located on-site. Each power source (the feeds from Class IV and the diesel generators) is physically and electrically independent up to the point of connection to the Class III buses. This improves the reliability of Class III power, making it available even in the presence of partial loss of Class IV power sources.

If the Class IV power source for a unit fails completely, it is still possible to obtain Class IV power from other units in a multiple-unit station. Once the standby generators are started, they will provide power to systems supplied by the Class III power source, ensuring that these critical systems remain functional.

Some typical systems supported by Class III power sources are listed in Table 5.

Table 5 - Equipment supported by Class III power supplies.

Auxiliary boiler feed pumps
Auxiliary condensation extraction pumps
Shutdown system cooling pumps
Turbine turning gear
Heat transport feed pumps
Moderator circulating pumps
Class I power rectifiers
Fire water pumps
Emergency core coolant injection pumps
Instrument air compressors
End shield cooling pumps
Service water pumps

The voltage level of Class III power is 4.16 kV, and its capacity can range from 6 to 8 MWe.

3.4.4 Class IV

Of the four classes of power sources in a NPP, Class IV supplies loads that can tolerate infinite interruption. This power can come from two sources. During normal operation, Class IV power is obtained from the main generator through the unit service transformer (UST). Using power

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

produced internally by the plant's own generator minimizes the potential impact of disturbances from the grid. Class IV power can also be obtained from the grid through the station service transformer (SST) when the UST becomes unavailable.

It is important to mention that even though Class IV power supplies the entire station during operation, it is not actually required for safe reactor shutdown, although the unit will be shut down immediately upon experiencing the loss of its Class IV power source.

The loads normally supplied by Class IV power are systems which can tolerate long-term power outages without affecting the safety of equipment, personnel, or the public. These loads are not essential to satisfy fuel cooling requirements following a reactor or turbine trip, but are essential for operation of heat sinks above the shutdown level of reactor power. Some typical systems supported by Class IV power sources are listed in Table 6.

Table 6 - Equipment supported by Class IV power supplies.

Main boiler feed pumps
Main heat transport circulating pumps
Condenser cooling water pumps
Generator excitation
Heating and ventilation equipment
Normal lighting systems

As can be seen from Table 6, many important systems in a CANDU plant are supplied by Class IV power sources, and the loss of Class IV power is considered to be a major incident. The preferred voltage levels for Class IV systems are 13.8 kV, 4.16 kV, and 600 V.

3.5 Load Transfer among Different Buses

As shown in Tables 3 to 6, NPP system loads are distributed among the various buses based on their size and importance to system safety. Although a detailed examination of each load is beyond the scope of this chapter, Fig. 6 provides an illustrative load diagram for the Class IV and Class III power buses.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

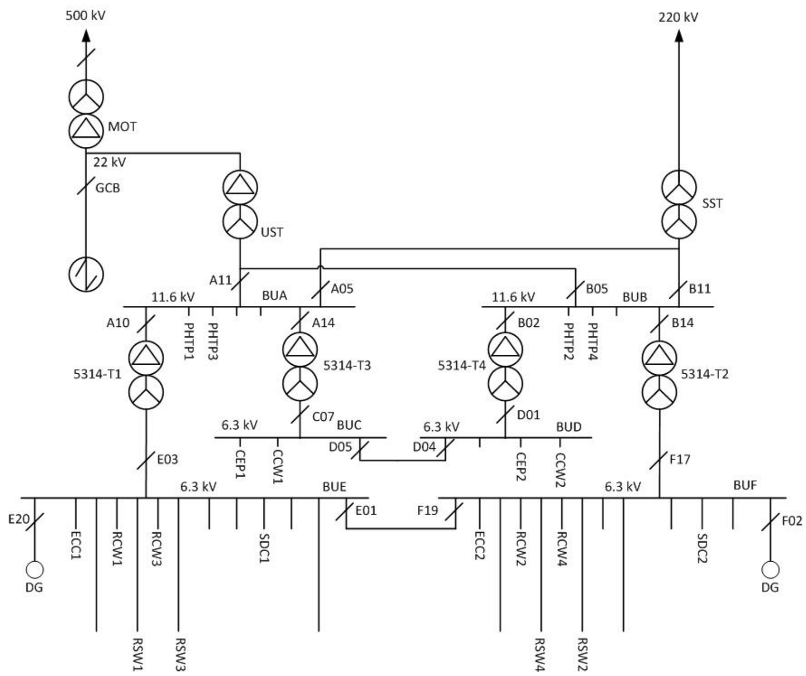


Fig. 6 - Load distribution on the Class IV bus in a CANDU plant.

Under certain circumstances, it is desirable to shift loads from one source to another. There are three modes of load transfer:

- parallel transfer
- fast transfer, and
- slow transfer.

These specific transfer schemes are used at the upper voltage level of Class IV to prevent reactor trip and maintain generation production.

The *parallel transfer* mode consists of two steps: (1) parallel the new power source to the existing one, and (2) remove the existing one to complete the transfer. A *fast transfer* switches the load quickly (within two power cycles) so that little interruption is observed. The *slow transfer* operates after the voltage has decayed to approximately 40% to limit the maximum voltage that could be applied to a connected load upon re-energization and can be used only if the supply transformers can tolerate the inrush currents and if the voltage drop does not prevent loads from being re-accelerated to nominal speeds.

Class IV transfers are manually initiated for normal transfers after start-up or before shutdown and are automatically initiated for reactor trips, turbine-generator trips, or loss of the transmission system. These transfers are accomplished by operating the incoming circuit breakers on the primary Class IV distribution buses to transfer the sources between the unit service transformer and the system service transformer.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

Automatic transfer systems are also incorporated into Class II. They monitor the operation of the power inverters and under certain conditions, transfer Class II distribution buses to alternative supplies directly from Class III. These transfers operate within each channel or division of Class II.

There are no transfers in the Class I system because each channel's batteries are charged through two 100%-capacity rectifier-chargers which share the load.

There are no transfers in Class III or in the EPS systems, although it is possible to connect the Odd and Even main distribution buses manually when, following a loss of Class IV power, only one standby generator in the system is operating.

Manual source selection is provided for Class I and II power conversion and distribution to address the condition when, after a loss of Class IV power, only one standby generator is available to power one Class III division.

3.6 Standby Generators (SGs)

To maintain power to safety, safety support, and heat-sink systems following loss of Class IV power sources, CANDU stations contain additional on-site power sources. One type is known as *standby generators*. These generators are not required to be seismically qualified.

This power source is based on two or more generators driven by diesel engines or combustion turbines (in the case of Ontario Power Generation). As shown in Figs. 4 and 6, a generator supplies Class III AC power to each Odd and Even bus at a 6.3 kV level. These generators are supplied with enough fuel to keep the diesel engines running continuously for an extended period of time (up to one week depending on a continued supply of fuel). Standby generator systems have their own compressed air and DC power sources for start-up and will start automatically upon loss of Class IV sources to maintain power to safety and safety support systems. The SGs could form a seismically qualified distribution system, but the design has evolved to create a separate seismically qualified distribution system. The seismically qualified systems are connected to Class III because that is their preferred source of power and are isolated from Class III only when the seismically qualified power sources can provide the required power. The standby generators will also start whenever a loss-of-coolant accident (LOCA) signal is issued, but will not connect to the buses until a loss of Class IV power occurs. Standby generators should be up and running within 30 seconds after receiving a LOCA signal, picking up all designated loads within a further three minutes. One standby generator has sufficient capacity to supply the required loads.

Because of the critical roles played by standby generators, regular maintenance is critically important. This typically consists of starting each diesel generator periodically from the local control panel, paralleling it with the respective division of the Class IV supply, and letting the generators run for a specified minimum period of time.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

3.7 Emergency Power Systems (EPS)

The second set of alternative power sources in CANDU plants is known as *emergency power systems*. Unlike standby generator systems, these power sources must be seismically qualified [7], and they function completely independently of other power sources. Similarly to standby generators, the emergency power systems start automatically upon the loss of Class IV power and will also start on a LOCA signal. Under such circumstances, back-up generators provide power to the NPP's critical systems to enable reactor shutdown, monitoring, and decay heat removal. It is expected that the system should be up and running with its intended loads within three minutes.

The following background is relevant to design decisions affecting the EPS:

- Based on plant licensing conditions, a loss-of-coolant accident (LOCA) is a random event because the heat transport system is fully seismically qualified and a seismic event, another random event, is not postulated to occur in the first 24 hours after a LOCA. With 24 hours of operation of emergency core cooling (ECC) and other required safety support systems, a 20–30 minute break can be tolerated in ECC operation. This time is sufficient for the operators to transition from the main control room (MCR) to the SCA and to restart the ECC and the associated systems.

- A total loss of Class IV power coincidental with a subsequent loss of Class III power, both random events (except at Fukushima where Class III was incapacitated by the tsunami, which was induced by the earthquake, but this is a different set of design conditions), but without a LOCA, is a condition in which residual heat is removed from the reactor by means of steam generators and water from the dousing tank. Depressurization of the heat transport system is a precondition for this mode of heat removal. Valves for implementing depressurization and maintaining the required monitoring are powered from a UPS or by compressed air for some valves. There is sufficient time for the operators to initiate the EPS to supplement the dousing tank reserve with an emergency water supply (EWS).

3.8 Grounding and Lightning Protection

The grounding system is required to prevent physical injuries and equipment damage in case of a fault and to minimize electromagnetic effects from ground fault currents as well as to prevent interference and to protect equipment from lightning strikes.

Lightning protection is required so that equipment related to the safety of the nuclear power plant continues to operate and important monitoring devices continue to function when lightning hits facilities or power lines.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

3.9 Control of Electrical Loads

Generally, in a typical CANDU power generating station, the electrical loads are remotely controlled using the control logic (relay logic) and interposing circuits, both powered from 48 V DC Class I. The output from the control logic is hard-wired to the switchgear and motor control centre (MCC) control circuits or to the terminals of a solenoid valve when the valve is controlled directly.

Major loads have their mode of operation (ON, AUTO, or STANDBY) selected by the operator from the main control room (MCR) or the secondary control room (SCA). In the AUTO mode, the load will augment the already running load(s) when the process demand exceeds the capacity of the running load(s). In the STANDBY mode, the load will replace the normally running load when the latter fails to operate.

3.9.1 Loads powered from switchgear

Power to the various loads is switched ON and OFF by an individual circuit breaker at the selected voltage level. The circuit breaker protective relays may be mounted within the breaker cell, and the relays interposing between the breaker control circuit and the load's control logic are located in separate cubicles or cells, called the *relay and terminal* (R&T) section, adjacent to each group of circuit breakers.

A typical switchgear control circuit operates from the 250 V DC power source provided by the Class I batteries. The circuit is used to:

- Provide power to the operation of stored-energy devices which operate on the close and trip mechanisms of the circuit breaker.

- Close and trip the circuit breaker in response to commands from the:
    - Unit operator;
    - Process control system;
    - Power circuit protective relays.

Operation of the close and trip circuits requires momentary signals. The circuit breaker controls require manual local reset following a trip due to the operation of power circuit protective relays.

3.9.2 Loads powered from the MCC

Power to these loads will be switched ON and OFF by contactors in individual combination starters. The relays interposing between the contactor control circuit and the load's control logic are located in the relay and terminal (R&T) section adjacent to each group of combination starters.

The circuit breaker in the combination starter is manually operated and, except for

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

maintenance, remains in the closed position. A typical MCC control circuit operates from the 120 V AC power source provided by the starter's step-down transformer. The circuit is used to energize and de-energize the contactor in response to commands from the:

- Unit operator;
- Process control system;
- Circuit breaker protection and overload relays.

To remain energized, the contactor requires a signal to be maintained. The circuit breaker requires a manual local reset following a trip due to the operation of power circuit protective functions built into the breaker.

3.9.3 Class IV and Class III loads

Typical types of interfacing circuits are:

- MCC and switchgear:
  - Off/On;
  - Off/Auto/On;
  - Off/Standby/On;
  - Off/Standby/Auto/On.
- MCC only:
  - Motorized valve with non-auto control;
  - Motorized valve with auto control.
- Other:
  - Solenoid valve with non-auto control;
  - Solenoid valve with auto control.

3.9.4 Class II and Class I loads

Loads energized from the Class II and Class I (UPS) MCCs or panels perform either special safety-related or personnel/equipment protection-related functions. The control modes are therefore limited to OFF/ON or OFF/AUTO/ON and, in the case of motorized valves, to OPEN/CLOSE or OPEN/AUTO/CLOSE and operate in the same way as the Class III and Class IV loads with the same type of controls.

3.9.5 EPS loads

Loads energized from the EPS are controlled in the same way as when they were energized from Class III, II, and I or will be limited to manual OFF/ON controls.

3.10 Summary

The safety and operating reliability of a CANDU NPP depend heavily on availability of electrical

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

power to ensure proper operation of its various systems. The electrical power system inside the plant is divided into four classes: Class I, II, III, and IV. Energy for Class I is stored in batteries and can be obtained from the rectified power of Class III sources. Class II power is obtained from Class I through DC/AC inverters or directly from Class III. Standby generators provide alternative power to Class III and EPS systems. Normally, the plant obtains power from its own unit through a UST. It is also possible and permitted to operate the plant with Class IV power supplied through an SST. When a unit stops producing electrical power, power is drawn from neighbouring units through switchyard connections. This may require manual re-configuration (depending on the event) to supply the shutdown unit(s) from the running unit(s) to remove decay heat. When these power sources are not available, grid power can be used to power Class IV through the SST. Once Class IV power is lost, the reactor must be shut down immediately, and heat sink systems are powered from Class III standby generators or the EPS.

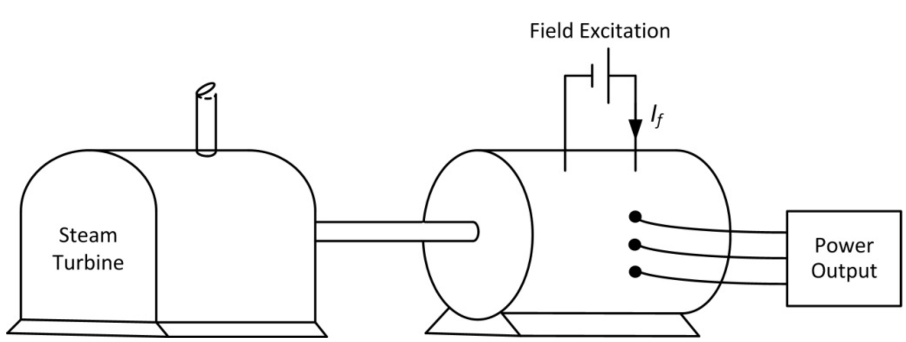
In addition, CANDU stations are also equipped with two sets of long-term on-site power supplies, at least one of which is seismically qualified, which are driven by diesel engines. Within the same class, the Class IV, Class III, and some Class II loads in the plant are distributed on multiple and separate buses depending on the number of loads, their power requirements, and the plant's Odd/Even bus philosophy. Class I and Class II power to I&C circuits is supplied through three channelized distribution systems from channelized and independent energy storage and conversion systems. Because Class IV buses are capable of receiving power from either of two supplies and because automatic transfer of supplies is provided on sensing loss of power, reliability of power is ensured, and plant operating safety is increased.

4 Main Electrical Components in a CANDU Plant

4.1 Generators

4.1.1 Basic principle

Electricity output from a CANDU nuclear power plant is generated by a synchronous generator. The generator shaft is directly coupled to that of the steam turbine. The function of the generator is to convert mechanical energy from the turbine to electrical energy to supply electrical loads. A simple illustrative diagram is shown in Fig. 7.



©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

Fig. 7 - Turbine and generator set.

The principle of a generator is based on Faraday's law of electromagnetic induction. The main parts of a generator are a stationary iron core and winding, known as the stator, and a rotating iron core and winding, known as the rotor. When the rotor winding is energized through the field excitation circuit, as the turbine rotates the rotor, a rotating magnetic field is created. The excitation current is supplied to the rotor winding through slip rings. The rotating magnetic flux induces a potential in the stator winding. An illustrative diagram is shown in Fig. 8.

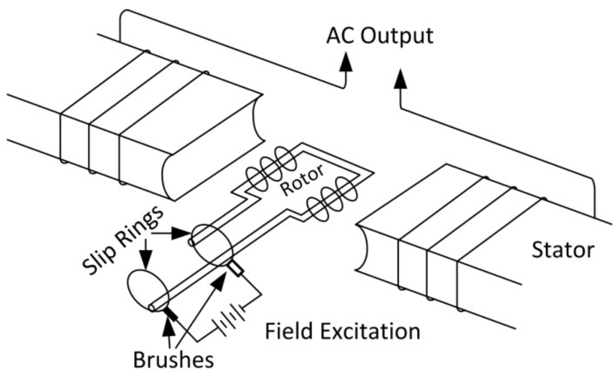


Fig. 8 - Illustrative diagram of a synchronous generator.

Due to the relative positions of the magnetic flux and the stator winding, as the rotor turns, the induced voltage will take on a sinusoidal form. The frequency of the generated voltage will be directly related to the rotational speed. For the two-pole (N-S) machine shown in Fig. 9, one full revolution will produce one full cycle of a sinusoidal wave. If the number of pole pairs on the rotor is increased, a full revolution of the shaft will produce multiple cycles at the electrical output. In other words, it is possible to reduce the rotational speed of the turbine, but still to generate the desired frequency in the electrical output, by increasing the number of pole pairs.

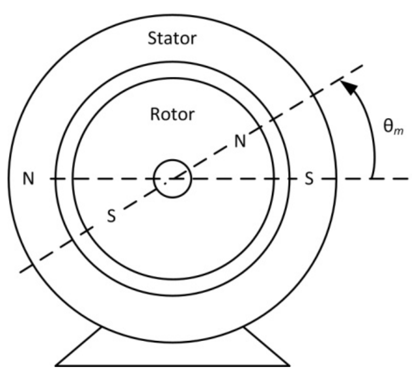


Fig. 9 - A two-pole (one pole pair) synchronous generator.

The relationship among the speed of rotation (n rpm), the output frequency (f Hz), and the number of pole pairs (p) can be stated as follows:

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

$$n = \frac{60f}{p}.$$

The word *synchronous* means that the magnetic field rotates in synchronism with the rotor. When the stator windings are placed 120° apart as shown in Fig. 10, a three-phase voltage can be generated.

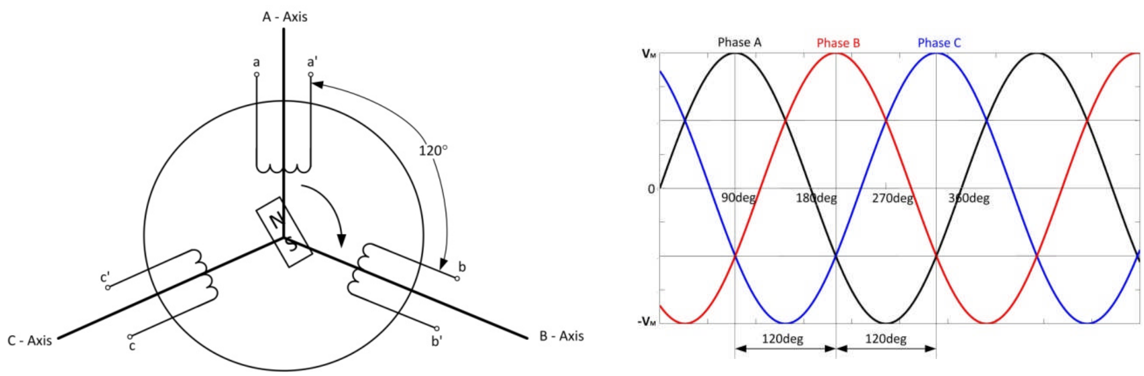


Fig. 10 – Three-phase synchronous generator.

When a load is connected to the output of the stator winding, the generator will transfer the power to the load.

Assume that the currents from each phase can be represented as:

$$i_A = I_M \sin \omega t$$

$$i_B = I_M \sin(\omega t - 120°)$$

$$i_C = I_M \sin(\omega t - 240°).$$

The active power output delivered to the load at each phase can be calculated as:

$$P = i_M v_M \cos \theta_m \quad \text{MW}$$

The reactive power is

$$Q = i_M v_M \sin \theta_m \quad \text{MVar}$$

where i_M and v_M are the phase current and phase voltage.

The angle θ_m is the phase difference between the voltage and the current at the generator output. Hence, the total real and reactive power output from all three phases can be expressed as:

$$P_{total} = 3P = 3 i_M v_M \cos \theta_m \qquad \text{MW}$$

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

$$Q_{total} = 3Q = 3i_M v_M sin\theta_m \qquad \text{MVar}$$

The rated power is

$$P_{rated} = 3i_M v_M \quad \text{MW}$$

The power factor (*pf*) is

$$pf = cos\theta_m$$

Typically, the power factor is maintained between 0.8 and 0.9. The frequency of the generated power is controlled by a governor on the turbine, and the generator output voltage is controlled by the field excitation through an automatic voltage regulator.

4.1.2 Generators in a CANDU plant

There are several generators in a CANDU plant: (1) the main generator; (2) the standby generators; and (3) the generators in the emergency power system.

The main generator converts the mechanical power from the turbine to electric power that is delivered to the grid to supply power to customers. Typical specifications of a main generator are listed in Table 7.

Table 7 - Characteristics of the main generator in a CANDU plant.

Capacity	817 MVA
Rated output power	728 MW
Output terminal voltage	22 kV
Power factor	0.9 lagging
Frequency	60 Hz
Number of phases	3
Number of poles	4
Rated speed	1800 rpm
Excitation system	Static thyristor exciter
Stator cooling	Water
Rotor cooling	Hydrogen

Typical specifications of the standby generators and the emergency power generators are listed in Tables 8 and 9 respectively.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

Table 8 - Characteristics of the emergency power system generator.

Rated output power	1.6 MW
Rated current	183 A
Output terminal voltage	4.16 kV
Power factor	0.8 lagging
Frequency	60 Hz
Number of phases	3
Number of poles	6
Rated speed	1200 rpm

Table 9 - Characteristics of the generator in the Class III power system.

Rated output power	8.2 MW
Output terminal voltage	4.16 kV
Power factor	0.8 lagging
Frequency	60 Hz
Number of phases	3
Number of poles	12
Rated speed	600 rpm

4.1.3 Excitation system

To create a magnetic field inside a synchronous generator, separate windings and an electrical power source must be used. This part of the generation system is known as the *excitation system* and is shown in Fig. 12. The excitation system is essentially a controllable DC source. By adjusting the excitation system output voltage, the output voltage level of the generator can be controlled, and hence the reactive power output. Because the excitation current must be delivered to the windings on the rotor, slip rings are used.

Once the generator is running, power for the excitation system can be obtained from the excitation transformer, which is energized from the Class IV distribution system. The power source can be either the SST or the UST. However, AC power from the generator must be converted to DC before it can be delivered to the rotor windings. In the past, a DC generator coupled to the synchronous generator shaft was used to produce DC power for the excitation system. Nowadays, this conversion is accomplished by a thyristor-based rectifier. Unlike a DC generator, this conversion process has no moving parts; hence, it is often referred to as a *static thyristor-based excitation system*.

During normal operation, the excitation system is often used to (1) control the output voltage level of the generator, and (2) adjust the reactive power output of the generator. A feedback control system, known as an excitation control system, is also used to ensure that adequate excitation voltage is applied to maintain the desired generator output voltage level and the reactive power output. These functionalities are essential to improve the reliability of the generator system.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

In the event of an emergency, the excitation system can also be used to provide additional means to improve system stability. For example, when a fault has occurred on the transmission system, the output voltage of the generator can decrease unexpectedly. The excitation system can be used to slow down this voltage collapse, thus improving system stability. If a short circuit in the generator or at the generator output terminal is detected, the excitation system can cut its power immediately to drive the generator output voltage to zero, preventing further damage to the generator.

In a CANDU plant, an excitation transformer is used to step down the generator output voltage from 22 kV to 850 V before sending it to the thyristor-based rectifier. However, different plants may have different output voltage levels. An illustrative diagram of an excitation system is shown in Fig. 11.

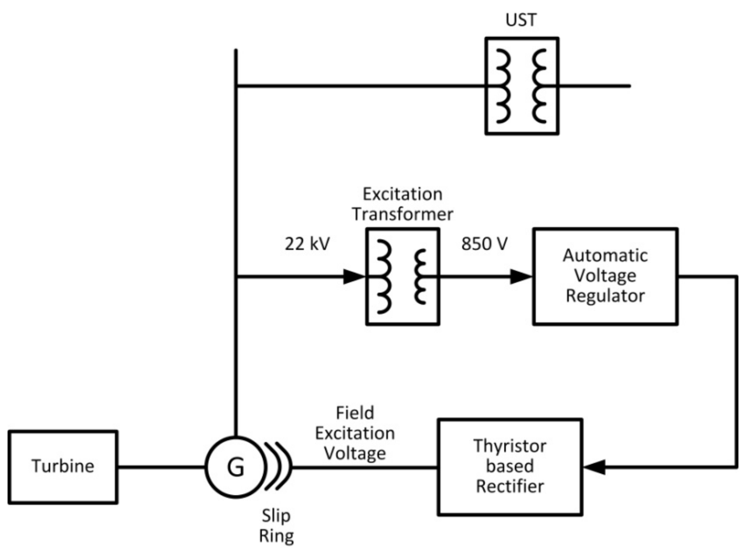


Fig. 11 - Conceptual diagram of a static thyristor-based excitation system.

To start the generator, a separate excitation system must be used. The details will be omitted here. Once the generator starts to operate, a portion of the generated power is used to provide the excitation for its magnetic field. The excitation power is obtained by converting a portion of the 22 kV generator output to 850V AC voltage. This voltage is further regulated through an *automatic voltage regulator* (AVR) and subsequently sent to a thyristor-based static rectifier to convert the AC voltage to DC voltage before sending it to the rotor through the slip ring. The excitation system for the SGs and EPGs is different in that they must start when no additional sources of AC power are present.

4.1.4 Excitation transformer in a CANDU plant

The excitation transformer is a three-phase transformer. Delta (Δ) connections are used on both primary and secondary sides. Specifications of one such transformer are listed in Table 10.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

Table 10 - Characteristics of an excitation transformer.

Rated capacity	6,300 kVA
Voltage ratio	22,000 V/850 V
Rated currents	165 A/4,279A
Loss at no load	10,858 W
Loss at full load	46,678 W
Cooling method	Air-cooled

4.1.5 Cooling and protection systems

As electric current passes through the generator windings, heat is produced in both the rotor and the stator. To maintain a safe operating temperature, adequate cooling must be provided. For generators in CANDU plants, water cooling is used for the stator winding, whereas hydrogen is used to cool the rotor winding and the iron cores of both the rotor and the stator.

The main part of the water cooling system consists of two centrifugal pumps and two heat exchangers. The pumps maintain a steady flow of cooling water through the stator windings. The water pressure is controlled by means of a pressure control valve which keeps the loop pressure around 150–200 kPa. The water temperature is adjusted by means of a proportional valve which mixes hot water from the outlet with water cooled by the heat exchanger. The objective is to ensure that the temperature of the water coming out of the stator is around 46°C. The two pumps, rated at 75 kW, are powered by the Class IV electrical system. If cooling water is lost, the generator will shut down immediately. Demineralized water must be used, and dissolved oxygen must be controlled.

The reasons for using hydrogen as a coolant for the rotor and generator are its relatively high thermal conductivity, low density and viscosity. The former property allows effective cooling, and the latter property reduces the windage losses associated with the generator rotor rotation. The main parts of the cooling system are the hydrogen supply unit, the hydrogen cooling heat exchanger units, and the hydrogen leakage detection system. Another critical part is the generator oil seals, which prevent hydrogen from escaping and causing a fire or explosion.

Hydrogen stored at high purity (98%) is injected into the generator air gap between the stator and the rotor. The pressure is controlled through a pressure regulator set at 414 kPa. The humidity of the hydrogen is controlled by a gas dryer heater. Four heat exchanger units are located at the four corners of the generator to maintain the outlet temperature of the hydrogen at 40°C. To prevent leakage, the generator is tightly sealed. Due to the flammable nature of hydrogen, care must be taken to avoid any chance of friction-induced sparks during filling and emptying of hydrogen. Systems removing or adding hydrogen must be grounded (possibly even the individuals using them) to eliminate the potential for sparks due to build-up

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

of static electricity or from energized equipment. Several hydrogen leakage detectors are installed in the vicinity of the generator.

4.2 Transformers

4.2.1 Basic principles

The main function of a transformer is to convert AC electric energy from one voltage level to another while minimizing the losses in the transformation process. A typical transformer has two independent windings. One is referred to as the primary winding, and the other as the secondary winding. These windings are coupled through a magnetic circuit in the iron core of the transformer. Ferromagnetic materials are used to construct the core to confine the magnetic flux inside. An illustrative diagram of a transformer is shown in Fig. 12. It is interesting to point out that, between the primary and the secondary, there is no direct electrical connection.

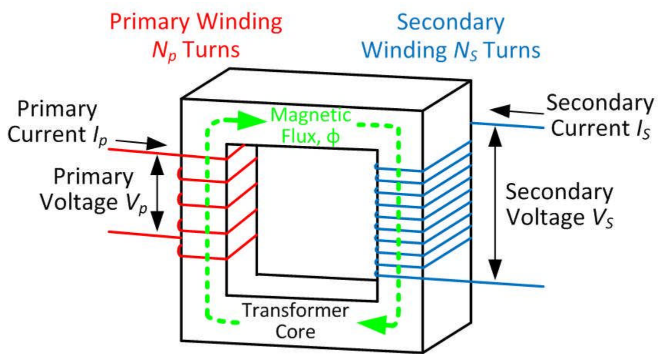


Fig. 12 - Basic operating principle of a transformer.

The operating principle of a transformer can be described as follows: the current in the primary winding creates an alternating magnetic flux, ϕ, inside the core. The strength of this flux is proportional to the current, I_p, as well as to the number of turns in the primary winding, N_p. On the secondary side, based on Faraday's law of induction, a potential, V_s, will be induced in the secondary winding. The level of this induced potential is proportional to the strength of the magnetic flux, ϕ, which is a function of the current, I_p, as well as of the number of turns in the secondary side, N_s. Therefore, if N_s is larger than N_p, the voltage at the secondary will be higher than that at the primary; such a transformer is often referred to as a *step-up transformer*. A transformer with the winding turned the other way around is known as a *step-down transformer*.

Most electrical power systems are three-phase systems. The power generated from a three-phase synchronous generator must be connected to three-phase transmission lines through a three-phase transformer. In fact, a three-phase transformer will have three primary windings and three secondary windings. A three-phase transformer is formed by proper connection of these windings on both the primary and secondary sides. For simplicity, only single-phase

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

transformers are described in this chapter.

If the circuit in the secondary side is closed (through a load directly, or through transmission lines), a path will be formed for the current, I_s, to flow through. Assume that all the flux serves to couple the primary and secondary windings; therefore, the flux, ϕ, will be equal on both sides:

$$N_p I_p = N_s I_s.$$

Furthermore,

$$V_p I_p = V_s I_s.$$

Therefore, it becomes clear that:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s},$$

or

$$V_s = \frac{N_s}{N_p} V_p.$$

The ratio (N_s/N_p) is known as the *turn ratio*. When the turn ratio is greater than unity, the voltage level on the secondary side will be higher than that on the primary side, and vice versa. Because a transformer is a passive device, the current is inversely related to the turn ratio; the current decreases as the turn ratio increases and increases as the current ratio decreases.

The product of the current and the voltage permitted to be applied to the transformer is known as the *transformer rating*. The rating relates directly to the conductor size, core, and heat dissipation capability.

Like any other electrical apparatus, a practical transformer will be less than 100% efficient. Several sources contribute to these losses. The first is the ohmic losses in both primary and secondary windings due to the resistance of the coils. These are also called copper losses. The second loss occurs as a result of hysteresis and eddy currents in the core. This type of loss is normally independent of the currents in the transformer and is commonly referred to as iron loss. These losses normally take the form of dissipated heat. In practice, the heat must be evacuated through cooling systems. Transformer windings are often submerged in mineral oil to carry away the heat to be dissipated at the fins on the transformer covers. To accelerate the heat dissipation rate further, forced air, forced oil, or water circulation can be used to increase heat transfer effectiveness. However, these added power devices will consume additional energy.

Even though most transformers work under principles similar to those described above, their

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

appearance can vary greatly. A typical transformer found in a nuclear power plant is illustrated in Fig. 13. The high-power terminals are located at the top of the transformer, where three isolated connections can be seen. Electric fans are used to create forced air circulation to increase the heat dissipation rate.

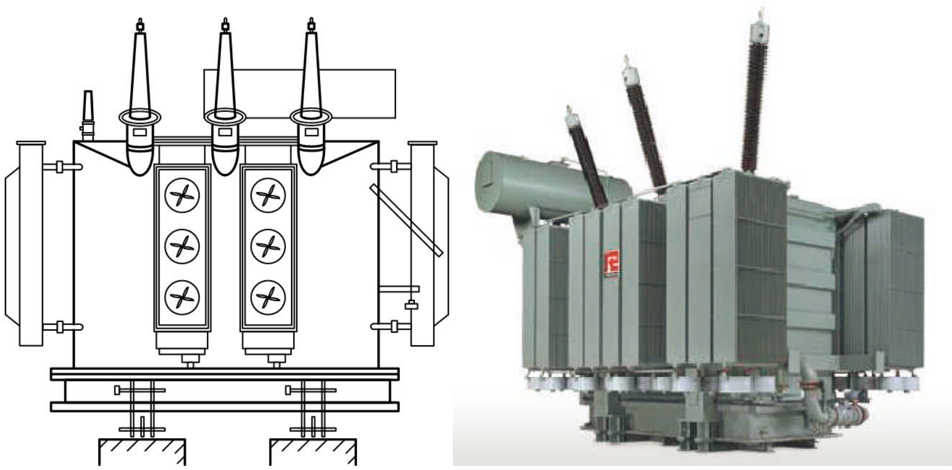


Fig- 13 - External appearance of a typical power transformer.

4.2.2 Major transformers in a CANDU plant

In a CANDU plant, there are many transformers serving different purposes. However, three main transformers deserve special attention:

- Main output transformer (MOT)
- Station service transformers (SSTs)
- Unit service transformers (USTs).

Their functionalities have been explained in Section 2, and their specifications are given in Tables 11 through 13.

Table 11 - Ratings of a main output transformer (MOT).

Rating	3 × 277 MVA
Primary-side voltage	22 kV
Secondary-side voltage	500 kV
Temperature (oil)	45°C
Temperature (winding)	65°C
Cooling method	Forced oil and forced air

Table 12 - Ratings of a station service transformer (SST).

Rating	60 MVA (natural cooling) 80 MVA (forced air cooling)
Primary-side voltage	220 kV
Secondary-side voltage	11.6 kV

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

Operating temperature range	50°C–75°C
Heat transfer medium	Oil
Cooling method	Natural or forced air

Table 13 - Ratings of a unit service transformer (UST).

Rating	60 MVA (natural cooling) 80 MVA (forced air cooling)
Primary-side voltage	22 kV
Secondary-side voltage	11.6 kV
Operating temperature range	50°C–75°C
Cooling method	Natural or forced air

4.3 Voltage and Current Transducers

4.3.1 Principles

High-voltage, high-current electrical parameters (in the kA and kV range) cannot be directly used for control purposes. To use these parameters in control and monitoring circuits, they must be transformed to a range suitable for these applications, generally in the ampere to milli-ampere and volt to milli-volt range. There are two groups of electrical quantities in a CANDU plant. The second, lower-value group is suitable for monitoring, control, and electrical protection purposes, such as input to a meter displaying the generator power output in the main control room, or input to a data acquisition system which captures the in-rush current of a circulation pump. High-voltage, high-current quantities cannot be directly connected to low-power devices without some type of conversion apparatus. To measure high voltages and large currents effectively, their electrical parameters must be converted to voltage and current ranges which are safe for use by measurement devices and human operators without the need for special protective equipment.

The devices that produce the corresponding low-level signals, which are proportional in value to the original high-power quantities, are known as *transducers*. Because voltages and currents are the two most important electrical quantities in an electrical distribution system, this section will focus mainly on voltage and current transducers. Only AC voltage and current transducers will be discussed because most of the high-voltage, high-current quantities are of this form. An importance difference between power transformers and voltage and current transducers is the requirements for accuracy and linearity. These requirements are much more stringent in the latter case.

A voltage transducer is essentially a transformer with a sufficiently small turn ratio, which converts a high-voltage signal to a low-voltage one. The high-voltage signal is connected to the

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

primary side, and the low-voltage signal is generated on the secondary side. As discussed in Section 4.2.1, transformers have the unique ability to isolate the high-voltage primary side from the secondary side electrically. The low voltage carries the same amount of information as the high voltage, but at a lower electrical potential, making it safer for maintenance personnel and for equipment designed to operate at lower voltage levels.

An illustrative diagram of a single-phase voltage transducer is shown in Fig. 14(a). When a high voltage, V_1, is applied, the transducer will produce a corresponding low voltage, V_2. The voltage ratio is determined by the turn ratio of the primary and secondary windings, i.e.,

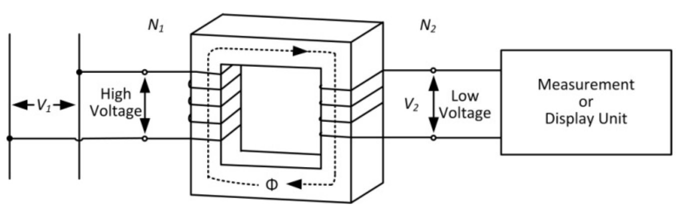
$$V_2 = \frac{N_2}{N_1} V_1,$$

where $(\frac{N_2}{N_1})$ is less than unity and represents the voltage reduction factor.

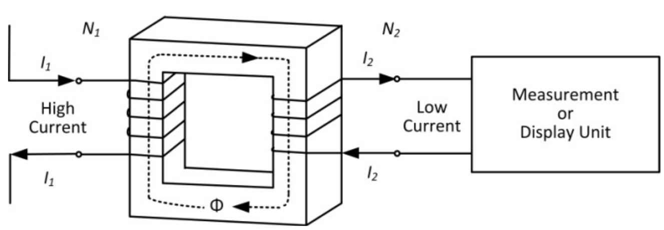
The principle of a single-phase current transducer is shown in Fig. 14(b). The relationship between the current on the primary side and that on the secondary side can be expressed as follows:

$$I_2 = \frac{N_1}{N_2} I_1,$$

where $(\frac{N_1}{N_2})$ determines the current reduction factor.



(a)



(b)

Fig. 14 - Principles of (a) voltage transducers; and (b) current transducers.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

4.3.2 Voltage and current transducers in a CANDU plant

There are many voltage and current transducers throughout the plant that provide information on voltage and current levels in real time for control and monitoring purposes. Four sets of current transducers are located at the generator output, each with a rating of 1,700A / 5A. There are also two voltage transducers at the generator output, both having a reduction ratio of 22kV/100V. Similar devices are also used for electrical protection of major transformers, such as excitation transformers. A capacitor voltage transformer is used for high-voltage measurement at the grid connection point to provide information necessary for plant operation, as well as for protective relaying.

4.4 Switches, Circuit Breakers, and Disconnect Switches

4.4.1 Concepts and operating principles

There are many electrical switches in a CANDU plant. The most common are those used to turn certain pieces of equipment such as lights, pumps, or instruments on and off. A switch that is turned to the on position (closed) allows electricity to pass through, whereas turning it off (opening it) breaks the electrical circuit and stops the flow of electrons. In a low-power environment, the switches are not much different from those in everyday use.

As voltage and current levels increase, the construction and operation of these switches becomes more complex. High-voltage or high-current switches are often known as circuit breakers, disconnect switches, and contactors. As the names imply, one of the important functions of such devices is to conduct or break the current flow in a circuit. There are two main scenarios which call for such actions: (1) to execute a control command, such as to start or stop a load, and (2) to cut off the current flow in an abnormal operating condition such as a short-circuit fault. A circuit breaker must be able to carry and to interrupt current as needed.

An illustrative diagram of an over-current protection circuit breaker is shown in Fig. 15. The breaker is connected in series with the circuit. If there is no manual tripping signal, or if the current is within the operating limit, the breaker remains closed. If either a manual tripping signal is issued (by pushing a button) or if the measured current exceeds the threshold, the tripping coil will generate a trip signal to open the breaker, thereby interrupting the current flow.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

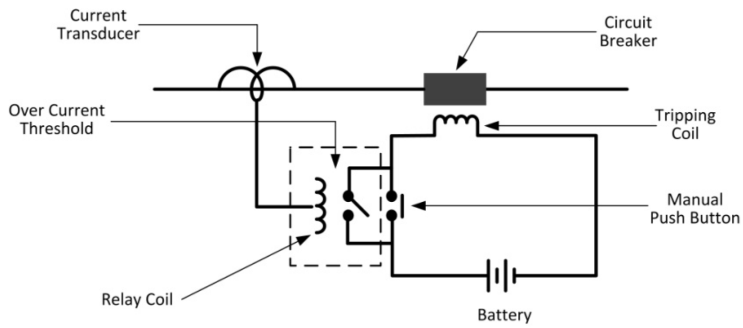


Fig. 15 - An over-current protection circuit breaker.

A significantly high voltage can be induced between the two contacts of the circuit breaker when it interrupts the current flow. As the contacts separate, the resistance between them increases rapidly, producing hot spots between the contacts. The high voltage between the contacts can also form a very strong electrical field. As the particles between the contacts become ionized, electric arcing occurs, which will prolong the time taken for the current to reach zero. To minimize the impact of short circuits and reduce wear and tear on the breaker contacts, the arc must be extinguished quickly. The breaker and bus bars must be designed to withstand the mechanical forces resulting from short-circuit currents. Depending on the duration of the short circuits, the amount of mechanical bracing may need to be increased.

Depending on the method of arc extinction, circuit breakers can be classified as:

- Air-break circuit breakers
- Air-blast circuit breakers
- Vacuum circuit breakers
- SF6 circuit breakers.

An air-break circuit breaker relies on the high-resistance interruption principle by rapidly lengthening the arc through an arc runner. The arc resistance is increased to such an extent that the arc can no longer be sustained. Such types of breakers are mainly used in low- and medium-voltage circuits.

In an air-blast circuit breaker, high-pressure air is blasted into the arc, blowing away the ionized gas between the contacts to extinguish the arc. The voltage and current that can be interrupted by an air-blast circuit breaker are normally higher than in an air-break circuit breaker. As its name implies, the contacts in a vacuum circuit breaker operate in a vacuum interrupter chamber. The arc is generated by ionization of the contact material, whereas in an air breaker, it is generated by the arc material as well as air ionization. Hence, in a vacuum, the arc is immediately extinguished once the voltage can no longer sustain the plasma created at

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

the contact. The cost of the vacuum circuit breaker is relatively high, and they are often used in circuits at less than 38 kV.

SF6 circuit breakers are the most common for high-voltage and high-current circuits. SF6 is short for sulphur hexafluoride, a gas which satisfies the requirements of an ideal arc-interrupting medium. SF6 gas has high dielectric strength and is colourless, odourless, and non-toxic, with high thermal conductivity. It is also highly stable and non-flammable and does not cause corrosion when in contact with the metallic parts of a circuit breaker. SF6 circuit breakers can be found in circuits with voltages ranging from 3 kV up to 1000 kV.

Circuit breakers should not be confused with disconnect switches. Disconnect switches do not have any arc-extinction capability and therefore cannot be used to interrupt a current flow. Such switches are instead used to provide another layer of protection for repair or maintenance crews, enabling them to isolate the section of a circuit being serviced. Disconnect switches can be operated either manually or automatically (in the case of motorized switches, such as a starter).

4.4.2 Switchgear in a CANDU plant

There are many types of circuit breakers in a CANDU plant that provide control and electrical protection functions. Circuit breakers are installed in the plant to facilitate operation and electrical protection of transformers or electrical distribution bus bars. An illustrative drawing of an arc-extinguishing breaker is shown in Fig. 16. SF6 circuit breakers are used for high-voltage switchyard circuits, whereas vacuum breakers can be used at medium voltage levels (11.6 kV/6.3 kV). These breakers can be operated manually, automatically, or by remote control. The major types of high-voltage circuit breakers in a CANDU plant are described in Tables 14 to 16.

Table 14 - Characteristics of SF6 circuit breakers at the generator output.

Voltage level	24 kV
Rated voltage	30 kV
Rated current	24 kA
Rated capacity	1,000 MVA
Breaker closing time	Less than 42 ms
Breaker opening time	Less than 42 ms
Arc extinction time	Less than 60 ms

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

Table 15 - Characteristics of vacuum circuit breakers on an 11.6 kV bus.

Voltage level	11.6 kV
Rated voltage	15 kV
Rated current	2,000–3,000 A
Rated capacity	1,000 MVA
Breaker closing time	45–60 ms
Breaker opening time	30–45 ms
Arc extinction time	5–17 ms

Table 16 - Characteristics of vacuum circuit breakers on a 6.3 kV bus.

Voltage level	6.3 kV
Rated voltage	8.25 kV
Rated current	1,200 A
Rated capacity	500 MVA
Breaker closing time	45–60 ms
Breaker opening time	30–45 ms
Arc extinction time	5–17 ms

Disconnect switches are often found in series with circuit breakers to provide additional protection for workers. A disconnect switch is used in series with the circuit breaker at the generator output. The rated voltage of this switch is 24 kV, the current is 24 kA, and the maximum short-circuit current is 160 kA. Note that disconnect switches are not used to interrupt current in circuits. They are used for isolation purposes (worker safety and load isolation), as well as to reconfigure a network. They are installed to provide additional safety measures for maintenance crews working on the power line. There are also fuses installed in many electric systems throughout the plant to isolate short circuits or unforeseen faults.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

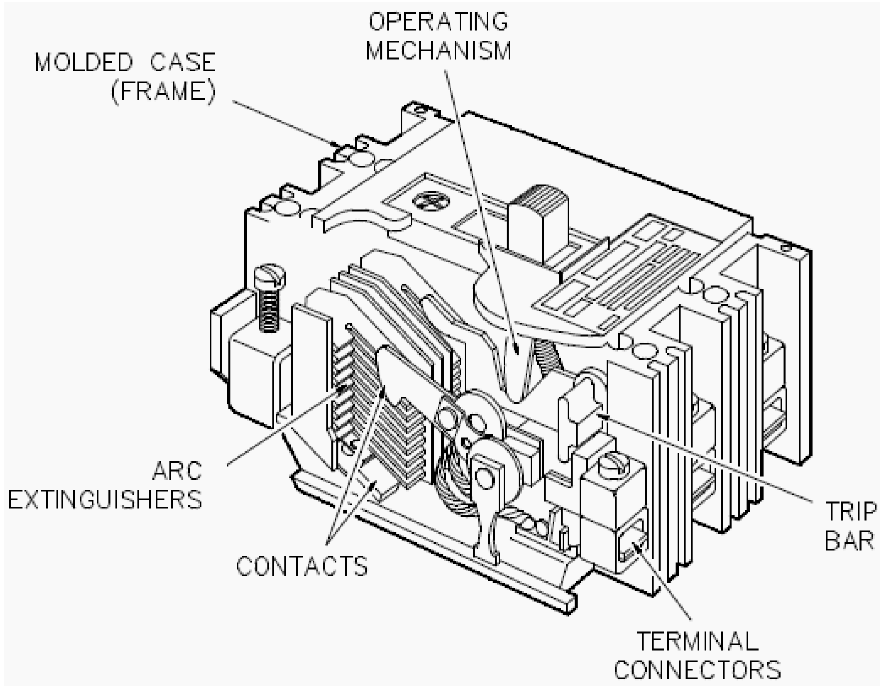


Fig. 16 - An arc-extinguishing circuit breaker.

4.5 Summary

A generator is an energy conversion device that converts mechanical energy from the turbine to electrical energy to supply the load. Together with the generator, there are several other auxiliary electrical systems in an NPP, such as circuit breakers, transformers, and voltage/current transducers. In this section, the general principles of these systems have been first explained, followed by information specific to CANDU NPPs. After completing this section, the reader should have a good understanding of how such systems operate, including knowledge of CANDU-specific applications.

5 Summary and Relationship to other Chapters

Even though the sole objective of a CANDU NPP is to produce electricity, this chapter is relatively independent of the other chapters in this book. To achieve a better understanding of the functionality of the different classes of power sources with respect to safety, the student should read Chapter 13 on Reactor Systems first to learn about the different safety systems and safety functions in a CANDU NPP.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

6 Exercise problems

1. State the reasons why an NPP is different from a fossil-fuel power plant in terms of its station power requirements.
2. From a power grid point of view, what criteria are used to select a suitable site for construction of a new NPP?
3. Why is off-site power so important to the safety of an NPP?
4. In your own words, explain the meaning of "odd/even power supplies".
5. List and define four classes of power used in a CANDU NPP.
6. State the original energy sources of the different classes of power sources.
7. State the sequences under loss of Class III power.
8. State the sequences under loss of Class IV power.
9. Why are batteries used in Class I power supplies?
10. Which class of power is used to charge the batteries in Class I power sources?
11. Explain the sources of power for each power class under both normal and emergency conditions.
12. Explain the role of grid power during the start-up and shutdown of a CANDU reactor.
13. What role do standby generators play in an NPP, and which class of power supply do they support?
14. What are the main differences between standby generators and an emergency power system?
15. Explain the different power sources that a CANDU plant has and the reasons for this.
16. List the main elements inside a generator.
17. Explain the principle of a synchronous generator used in a CANDU NPP.
18. What is the relationship between the number of generator pole pairs, the rotational speed, and the frequency of the voltage at the generator output?
19. Why is excitation important for synchronous generators?

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

20. How is excitation implemented in a CANDU NPP?

21. What is the function of the excitation transformer?

22. How is a generator cooled in a CANDU plant?

23. Under what conditions can the generator be connected to the power grid?

24. How are current and voltage measured in a CANDU plant?

25. What is the main function of a transformer?

26. Identify step-up and step-down transformers used in a CANDU plant.

27. Why are the coils in large-capability transformers often submerged in mineral oil?

28. What is the main function of the station transformer?

29. Why are protection devices important in a switchyard?

30. Explain the working principle of SF6 breakers.

31. What is the difference between a circuit breaker and a disconnect switch?

32. What is the function of a switchyard?

7 References

[1] Canadian Standards Association (CSA), Requirements for Electrical Power and Instrument Air Systems of CANDU Nuclear Power Plants (N290.5-06), 2011.

[2] CNSC Regulatory Document 2.5 Physical Design, Design of Electrical Power Systems for Nuclear Power Plants and Small Reactor Facilities (Draft stage).

[3] IAEA, Interaction of Grid Characteristics with Design and Performance of Nuclear Power Plants - A Guidebook, 1983.

[4] IAEA, Electric Grid Reliability and Interface with Nuclear Power Plants, No. NG-T-3.8, 2012.

[5] IEEE, Standard for Preferred Power Supply (PPS) for Nuclear Power Generating Stations (NPGS) Standard 765-2012, 2013.

[6] H. Ren, I. Dobson, B.A. Carreras, "Long-Term Effect of the *n*-1 Criterion on Cascading Line Outages in an Evolving Power Transmission Grid", IEEE Trans. on Power Systems, Vol. 23, pp. 1217–1225, 2008.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015

[7] CSA, General Requirements for Seismic Design and Qualification of CANDU Nuclear Power Plants, N289.1-08, 2008.

8 Further Reading

L.L. Grigsby, Power Engineering Handbook, CRC Press, IEEE Press, 2000 (ISBN-10: 0849385784).

IAEA, Design of Emergency Power Systems for Nuclear Power Plants, NS-G-1.8, 2004 (ISBN 92–0–103504–7).

P. Kiameh, Electrical Equipment Handbook: Troubleshooting and Maintenance, McGraw-Hill, 2003 (ISBN-10: 0071396039).

P. Kundur, Power System Stability and Control, McGraw-Hill Professional, 1994 (ISBN 0-07-035958-X).

J.D. McDonald, Electric Power Substation Engineering (2nd ed.), CRC Press, 2007 (ISBN-10: 0849373832).

9 Acknowledgements

The following reviewers are gratefully acknowledged for their hard work and excellent comments during the development of this Chapter. Their feedback has much improved it. Of course the responsibility for any errors or omissions lies entirely with the author.

Pel Castaldo
Alan Hepburn
Alek Josefowicz

Thanks are also extended to Diana Bouchard for expertly editing and assembling the final copy.

©UNENE, all rights reserved. For educational use only, no assumed liability. Electrical Systems – August 2015