1

Elements of a Power System

This chapter discusses the main elements of a power system that are particularly applicable to understanding the basic electrical configuration of a nuclear power plant.

1.1 The Alternating Current One-Line Diagram

A useful diagram to depict the alternating current (ac) system of a nuclear generating station is the one-line diagram (OLD) [2]. The OLD allows for the simplest representation of the main elements of a typical station and the interconnections among them. Figure 1.1 depicts a typical OLD for the high voltage and the medium voltage portions of a nuclear power station. Depending on the plant design and year of start of operations, the OLD may be somewhat different than the one depicted in Figure 1.1. The OLD of Figure 1.1 depicts a preferred approach to nuclear station design, as it offers enhanced independence for the safety-related busses.

While transformers AT1 and AT2 can be connected to the safety buses and also to the nonsafety buses, they are mainly intended to feed the safety-related busses. The only time that AT1 and AT2 are used to supply the plant nonsafety-related loads is for plant start-up or shutdown.

The plant normal operating conditions are with transformer AT feeding the plant nonsafety-related loads. Transformers AT1 and AT2 and normally energized and feed the safety buses, with both of these transformers being assigned to the two safety-related buses. Each one of the safety-related buses can be fed from an emergency diesel generator (EDG). Under normal plant operation, the EDGs are on standby condition.

After the generator starts up and synchronized to the grid, it is initially loaded with grid load to about 30% normal plant load, at which time the secondary side breakers of transformer AT are closed to feed the plant auxiliary loads.

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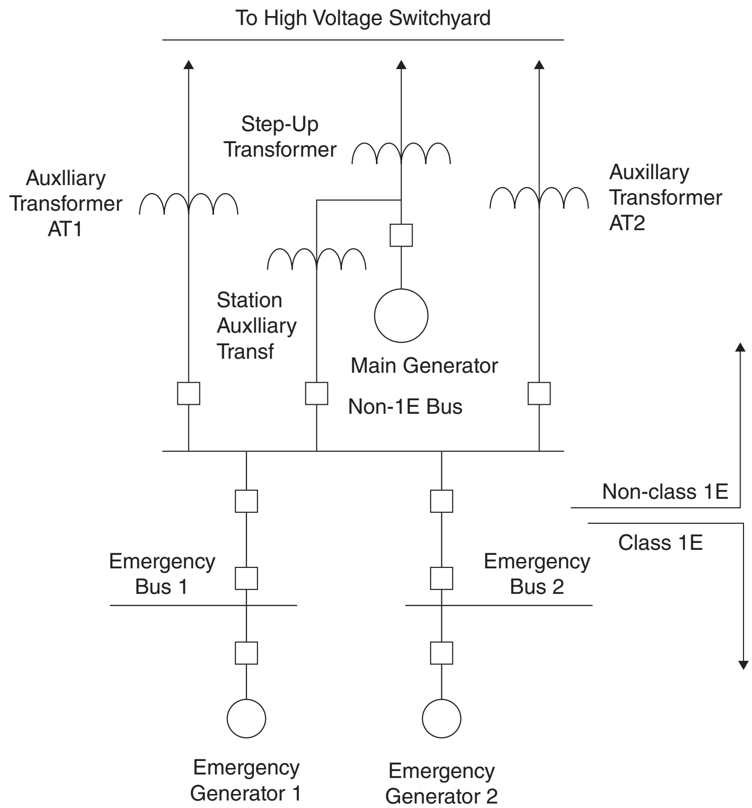

Figure 1.1 One-line diagram of nuclear station.

The preferred mode of starting up the station would be by synchronizing across the generator circuit breaker and feeding the station auxiliaries through transformer AT. An alternate approach, though less preferred, would be through either transformer AT1 or AT2, which would require a bus transfer to eventually feed plant loads through transformer AT.

Automatic bus transfers are necessary to prevent paralleling of two sources, which would impose undue short circuit stresses for the circuit breakers.

Thorough the plant start-up process, the two safety-related buses remain energized and are not subjected to any transfer operations, thereby eliminating the possibility of transients to be induced in the safety system.

The plant design allows for the possibility of testing the EDGs as required by the plant surveillance. The EDGs are tested once a month, and loads are picked up from the system for the period of test duration.

1.2 Basis for One-Line Representation

For a three-phase power system, in order properly represent it in an OLD, the system must be balanced, that is each one of the three phases must carry the same magnitude of current, and the currents must be at 120° from each other. As a result, the balanced three-phase system may be represented by just one of its phases, as they are the same to each other.

Percent and Per Unit Representation

In the definition of electrical power system values, a representation in percent (%) or per unit (pu) is more convenient than actual units such as ohm, volts, etc,

A base value must be introduced to show quantities in percent or per unit. For example, assuming a base voltage of 4.16 kV:

4.0 kV becomes 0.9615 pu, 96.15%
7.2 kV becomes 1.73 pu, 173%

The pu system is preferred because the product of two pu values results in pu, whereas the product of two percent values must be divided by 100 to express the result in percent.

Two base values must be selected to have all other values automatically determined. Generally, kVA and kV are selected. The term MVA refers to MVA for three phase and the term kV to voltage from line to line, then the term current refers to line current. Generally, power is understood to be three-phase power and voltage the line-to-line voltage, unless otherwise specified. A major exception occurs in the method of symmetrical components, where line-to-neutral voltage is used.

Per unit and percent values of transformer impedances are the same on either side of the unit (primary or secondary). Also, the per unit and percent values do not depend on the transformer connections (wye–wye, delta–wye…etc.)

The following relationships apply (see [4]):

Base current, $A =$ base kVA/1.732 base kV
$\Omega =$ (base voltage, $\mathrm{kV_{LN}})^2$/base MVA
Base impedance, $\Omega =$ (base voltage, $\mathrm{kV_{LN}})^2$/base MVA
Per unit impedance = actual impedance, Ω/base impedance, Ω

When dealing with unbalanced systems, symmetrical components must be used. In this method, the sequence components are always line to neutral or line to ground, as appropriate.

1.3 Main Electrical Components of Power Plants

Rotating Machines

Generators

Two types of generators are found in nuclear power plants: main generators that convert the mechanical power into electrical power and emergency standby generators utilized to provide electrical power to safety-related equipment when the normal power is not available [1,3]. This course places particular emphasis on the review of requirements for standby generators, as they are intrinsically involved in the performance of safety-related functions.

Motors

Most motors encountered in safety-related systems for nuclear power plants are of the AC induction type, constant speed. Some plants have AC variable speed drives, such as the feed water pumps for boiling water reactor type reactors. Motors for reactor cooling pumps are generally fitted with flywheels, to extend their operation when power is lost. Motors fitted with flywheels present special starting and protection issues.

DC motors are utilized for safety-related motor-operated valves.

Transformers

Distribution transformers are rated from 3 to 500 kVA, and below power transformers are those rated above 500 kVA.

In terms of insulation type, transformers can be oil cooled or dry type. The dry-type transformers include ventilated, cast coil, totally enclosed nonventilated, and sealed gas filled. Oil-insulated transformers are not utilized indoors, due to their intrinsic fire hazard.

Cables

Cables can be classified in accordance with their insulation ratings, which are as follows:

- medium voltage, rated 2001–35,000 V,
- low voltage, generally rated at 600 V, and
- instrumentation and control, rated below 600 V.

Switchgear, Distribution Panelboards, and Motor Control Centers

- switchgear, medium voltage, rated above 2000 V,
- switchgear, low voltage, rated 600 V, and
- panelboards and motor control centers, rated 600 V and below.

Buses

- *Phase-segregated buses*: Each phase is enclosed in a metallic enclosure, allowing for better isolation. Generally utilized for higher voltage types, such as the generator connection to the step-up transformer (19–24 kV).
- *Nonsegregated buses*: All phases are in the same metallic enclosure, generally utilized for voltages at 7.2–4.16 kV.

DC Batteries

Generally lead acid are the types of batteries found in nuclear plants. Voltages are between 24 and 250 V.

Battery chargers are provided to keep the batteries fully charged. The chargers provide the DC system load requirements whenever the normal ac input to the charger is available. Whenever ac power is available, the chargers provide the normal DC load and also the “trickle” current necessary to keep the battery fully charged.

Inverters

Inverters provide 120–240 V ac to safety loads requiring power when the main ac is not available, normally provided with autotransfer capabilities between available power sources.

Plant Loads and Their Characteristics

It is important to know how the plant loads will behave under variable voltage conditions. The modeling of plant loads is performed in accordance with the following guidelines:

- motors, constant impedance type for starting conditions, constant kVA type for running conditions and
- transformers, constant impedance type
  - lighting, load varies as the square of the impressed voltage,
  - heaters, load varies as the square of the impressed voltage, and
  - inverters constant kVA.

1.4 Transmission Lines, Switchyards, and Substations

The switchyard and associated substation are required to connect the power plant to the transmission grid, but are under the control of the power plant operators. The switchyard and its associated breakers, lines, and components are not considered safety related, though they may be considered important to safety.

Strategic arrangements are provided to increase reliability of operation. One common arrangement, which provides very high reliability, consists of three breakers in on lineup with the end breakers connected to a separate bus and two lines between the three breakers (this is the so-called “breaker-and-a-half” scheme).

Operation: Transmission lines are operated by the regional associations of grid operators. Of particular importance to the nuclear plant is the regulation of the supplied voltage, as it will affect the voltage at the plant and the operation of safety-related equipment. Special voltage relays are provided to disconnect the plant from the transmission grid, should the voltage excursion become intolerable for the proper operation of the safety equipment in the plant. (See [5] for extreme external events). The frequency of the transmission grid is also important, particularly when an EDG is paralleled to grid for test purposes.

Transmission Line Protective Relaying

Transmission line protective relaying is discussed under Chapter 9, “Interface of the Nuclear Plant and the Grid.”

Transmission Line Testing and Inspection

Transmission testing and inspection is discussed under Chapter 9, “Interface of the Nuclear Plant and the Grid.”

Questions and Problems

1.1 A prime requirement for the application of the one-line diagram is that the three-phase power system could be represented by just one phase. Could this representation be possible for a distribution system where there are numerous loads between one phase and the neutral? Explain your answer.

1.2 If a power system develops a phase-to-phase fault, is it possible to represent the faulted system with a one-line diagram? Explain your answer

1.3 What analytical technique is available to study unbalanced system conditions in a three-phase power circuit?

1.4 The one-line diagram (OLD) is utilized in the nuclear plant control room by the plant operators to review plant conditions under normal and emergency operation. In addition, a plant simulator is provided. The simulator is mainly used for training purposes. If there is a discrepancy between the simulator and the OLD, which one takes precedence? Explain.

1.5 A main generator circuit breaker is included in modern nuclear plant designs. Other plants have the generator connected directly to the switchyard through the step-up transformer. The main generator circuit breaker allows for isolation of the generator from the switchyard and also allows for availability of the plant station service transformer to feed the plant auxiliaries, without the need for fast bus transfer scheme. Would a generator breaker be considered particularly important to safe shutdown of the plant? Explain.

1.6 Plants that do not have a generator circuit breaker usually incorporate a fast bus transfer scheme to continue powering the station auxiliary buses in case of a plant trip. Why does the bus transfer scheme need to be fast? Provide a brief explanation.

1.7 From description of plant operation, it is not possible to keep the plant buses energized from two sources, as the short circuit capability of the breakers would be exceeded. Is this a normal plant design approach? If so, why?

1.8 If a nuclear plant operating at 100% output gets separated from the grid for a period time, say, for example, 5 min, it will need to trip and shutdown. This is due to the large excess between the reactor energy and the energy represented by the turbine steam bypass plus the plant auxiliary loads (about 6% of full load). The turbine bypass of the reactor energy is typically 25%. This situation is typical of all nuclear plants operating in the United States.

What if anything could be done to allow the plant to ride over the transient and keep the generator and reactor running until reconnection to the grid becomes possible?

1.9 Given:

Line to line voltage = 7.2 kV
Line to neutral voltage = $7.2/\sqrt{3} = 4/16$ kV
Three phase power = 21,000 kVA
$kVA_{1\Phi} = 7000$ kVA
Calculate pu values.

1.10 Later designs of nuclear plants have been fitted with a main generator circuit breaker, and some existing plants have been retrofitted to incorporate generator circuit breakers. Comment on the following:

- Have generator circuit breakers enhanced the operation of nuclear plants?, if so how?
- What safety aspects are enhanced by the generator circuit breaker?

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