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Auxiliary Power System and Protection Scheme for SMR Generating Stations

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1. Introduction

Due to many advantages such as flexibility, scalability, enhanced safety, reduced environmental impact and better compatibility with renewables, many countries, including the USA and Korea, are investing in the development and deployment of the Small Modular Reactors (SMRs). SMRs are seen as a promising option for meeting the growing energy demand while reducing greenhouse gas emissions and ensuring energy security. Electric systems that supply power to systems vital to safety are essential to the safety of nuclear power plants. Therefore, this paper propose a novel electrical control and protection scheme for the SMR generating stations based on the review of stakeholder requirements and available new technologies.

2. Requirements Review and Analysis

2.1 Special Feature of the Small Modular Reactors

The following special features of the SMRs should be considered in the process of design, construction and operation.

SMRs are smaller in size compared to conventional large size nuclear power plants, and they are designed to be modular. This means that they can be easily scaled up or down by the control of the number of modules, which provides greater flexibility to utilities. SMRs are designed with enhanced safety features, such as passive cooling systems that safely shut down the reactor without any onsite or offsite power sources, making them more resilient to natural disasters and other postulated events. SMRs have a lower environmental impact than large nuclear power plants, as they require less land and reduce greenhouse gas. Additionally, the modular design of SMRs allows for easier decommissioning and reduces the environmental impact of decommissioning.

Better Compatibility with Renewables: SMRs can be integrated with renewable energy sources like wind and solar to provide a more reliable and consistent energy supply. SMRs can provide a stable and reliable source of baseload power that can complement the variable output of renewable energy sources like wind and solar.

2.2 Conformity of Regulatory Requirements

The design of the offsite, onsite AC, and onsite DC electrical systems for SMRs shall conforms to GDC 2, GDC 4, GDC 5, GDC 17, GDC 18, and GDC 33 of the 10 CFR 50 Appendix A[1]. The GDC 17 defines that an onsite electric power system and offsite electric power system shall be provided to permit functions of structures, systems, and components important to safety. The GDC 18 defines that electric power systems important to safety shall be designed to permit appropriate periodic inspection and testing of important components and systems. Conformance with the requirements of IEEE Std. 308-2001, "Criteria for Class 1E Power Systems for Nuclear Power Generating Stations," is acceptable to the NRC staff for satisfying the NRC's regulations with respect to the design, operation, and testing of safety-related power systems for nuclear power plants, except for sharing of dc power systems at multi-unit nuclear power plants. The Class 1E system defined as the safety classification of the electric equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal or that are otherwise essential in preventing significant release of radioactive material to the environment by the IEEE 308.

If a small modular reactor (SMR) is designed to be passive and not rely on onsite or offsite power systems, it can be exempted from GDC 17 and 18, according to its design. The exemption from GDC 17 and 18 can be granted to a passive SMR design that does not depend on onsite AC power or offsite power systems to maintain fuel design limits, reactor coolant pressure boundary conditions, core cooling, or containment integrity during operational occurrences or postulated accidents.

3. Functional Analysis and Physical Allocation

3.1 Design Philosophies of Electric Power System

The electric power systems of nuclear power plants have several special features and design philosophies to ensure safe and reliable operation. The followings are major design philosophies.

a. Redundancy and diversity

Nuclear power plants have multiple redundant and diverse power systems to ensure that the plant can continue to operate safely even in the event of equipment failures or other unforeseen events. For example, they may have multiple backup power supplies, including diesel generators and battery banks.

b. Reliability and Robustness

Nuclear power plants are designed to be robust and reliable, with strong structures that can withstand severe weather events, earthquakes, and other natural disasters. They are also designed to withstand external threats such as terrorist attacks.

c. Safety systems

Electric power systems of a nuclear power plant have numerous safety systems that are designed to prevent accidents or mitigate their consequences. These systems include emergency power systems, station blackout (SBO) coping system, and extended loss of AC power (ELAP) system that prevent the release of radioactive material into the environment

3.2 Major Electrical Components and Systems

Fig. 1 is a typical key single line diagram for a generating station consisting of two SMR modules[2].

a. Main transformer

Main transformer transmit the power produced by the main generator(s) to the transmission grid. When the plant is shutdown, the main transformer back feeds the auxiliary loads form the grid power.

b. Unit Auxiliary Transformers;

Unit auxiliary transformer (UAT) supply power to the electrical loads of SMR. The UAT receives power from the generator bus and supply power to the medium voltage buses. If power unavailable from UAT even though offsite power is not lost, the power supply is automatically transferred to SAT(Standby Auxiliary Transformer).

When SMRs are built in multiples of two or more, it is possible to use the UAT of neighboring units as SAT instead of installing SAT

c. Medium Voltage Switchgears

Because SMRs are generally of small capacity (300 MW or less), the rated voltage of generator is medium voltage. The UAT steps down the generator voltage to the nominal voltage of medium voltage switchgear. According to the redundancy requirements of the auxiliary power system of a nuclear power plant, the medium voltage switchgear should be divided into two divisions.

d. Low Voltage Switchgears and MCCs

Small motors are rated at low voltage and fed from low-voltage switchgears or motor control centers (MCCs). The motor operated valves (MOVs) are also powered by the MCC. The number of low voltage switchgears and MCCs depends on the number of loads, and the principle is to install switchboards close to where the loads are concentrated. The low voltage switchgear and MCC must also be divided into two divisions.

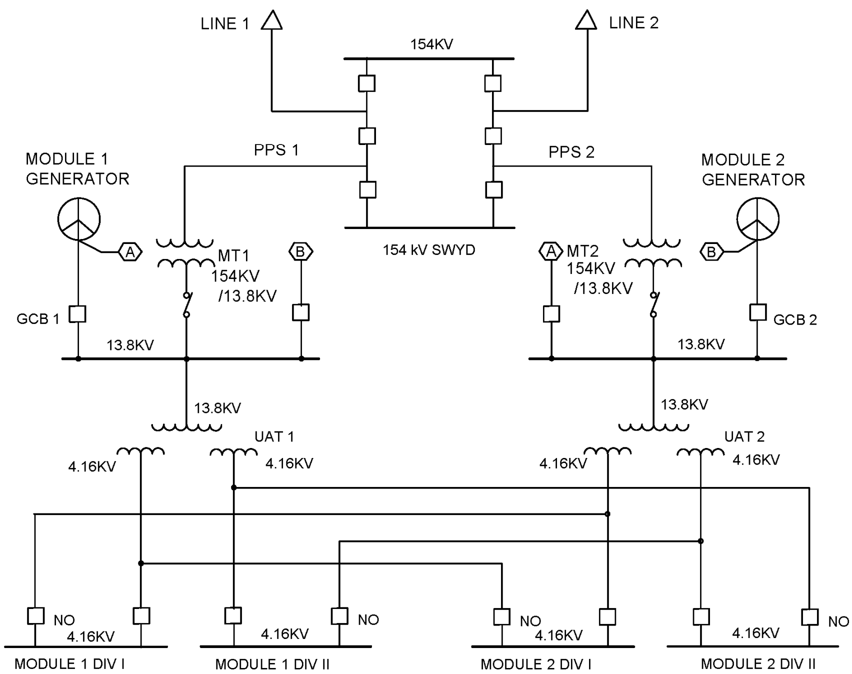

Fig.1 Typical key single line of multi module SMR

e. Emergency Power Systems

Each division of the important to safety 480V bus is supplied with emergency standby power from an independent emergency diesel generator (EDG). The EDG is designed and sized to have sufficient capacity to operate all the needed emergency shutdown loads, which are powered from its respective buses. Each EDG is rated at continuous operation and for short-time (2 hours) operation conditions.

f. 125V DC Distribution System

The direct current (DC) system provides DC power to valves operated by DC motors and various NSSS and BOP control and instrumentation systems. It also provides DC power to turbine/generator emergency loads under normal and abnormal operating conditions. The DC system also powers some emergency lighting.

Under normal operating conditions, the DC distribution system powers switchgear group controls, uninterruptible power supplies, inverters, diesel generator controls, relays, solenoid valves, and other electrical devices and components. In emergency operating conditions, when AC power is not available, batteries provide power for critical loads.

g. Instrument and Control Power System

The instrument & control power (IP) system supplies continuous, reliable, regulated AC power to the plant instruments and control equipment for their reliable operation.

The class 1E portion of the IP system provides a reliable AC power source during design basis events for control and instrumentation needed for safe shutdown of the reactor plant. The IP system provides continuous, reliable, regulated single-phase AC power to instrumentation and control circuits and man-machine interface (MMI) devices in main control room (MCR) which must remain operation during the momentary or complete loss of auxiliary power.

4. Design Definition

4.1 Defense in Depth (DID) and Implementation of AI and IoT Technologies

Defense in depth (DID) is a *fundamenta*l concept in the design of nuclear power plants (NPPs) to ensure the safe operation and protection of the public and environment. In the context of NPPs, DID refers to the use of multiple layers of defense to prevent and mitigate the consequences of accidents, failures, or other events that could lead to the release of radioactive material.

The electric power system of a nuclear power plant typically consists of two redundant and independent subsystems: two preferred supply systems (PPSs) and one emergency power supply system per division (on-site standby power)[3]. The PPS is the primary source of electricity for the plant, providing power to the safety related power systems under normal operation and abnormal conditions. The on-site standby power system, on the other hand, is designed to provide backup power to the plant's safety systems in case of a loss of offsite power. To apply DID principles to the electric power system design, several layers of protection are implemented, including:

a. Prevention

Measures to prevent or minimize the likelihood of events that could result in power system failures or outages, such as regular maintenance, testing, and inspection of equipment, and the use of robust and reliable components.

b. Detection:

Monitoring and surveillance systems to detect anomalies, malfunctions, or failures in the power system components or their support systems. Digitalized protective relays are implemented for the detection of failure and diagnosis of electric power systems.

c. Mitigation:

Backup systems and strategies to mitigate the consequences of power system failures or outages, such as redundant power supplies, batteries, emergency diesel generators, and other auxiliary power sources. Protection and backup protection systems are provided and AI and IoT technologies are implemented such as prognostics and health monitoring (PHM) and Deep Learning algorithms

d. Containment:

Physical barriers or protective measures to contain or limit the spread of any radioactive material released due to a power system accident or failure.

e. Emergency response:

Emergency plans and procedures to ensure the safe and timely response to any power system event, including the activation of emergency response teams and evacuation plans for the public.

4.2 Voltage Level Selection

The nominal voltage levels for the auxiliary power system is influenced by the type and size of load to be served, the distance power is to be transmitted, future load growth, equipment available for fault isolation, permissible voltage regulation, and the cost of utilization and service system equipment. North American countries use standard voltage levels recommended by ANS C84.1[4]. 13.8 kV or 4.16 kV are the voltages commonly employed in medium voltage systems. Low-voltage systems that supply power to small motors and heaters, etc., often choose 480V low voltage.

Countries in Europe, the Middle East, and Africa use standard voltage levels recommended by the IEC60038 standard[5]. 11 kV or 6.6 kV are commonly used voltages in medium voltage systems. 400V (50Hz system) or 480V (60Hz system) is the standard voltage for low voltage systems that supply power to small motors and heaters.

4.3 Ratings and Specifications of Major Equipment

a. Main Generator

According to NEMA MG-1, generators are designed to operate at ±5% of their rated voltage[6]. Switchyard bus voltage may run 5% above or below nominal voltage. Thus, the range of voltage can be ±5% from rated voltage, for the generator and for the switchyard bus. The maximum voltage will determine the maximum short circuit current, while the minimum voltage will determine the lowest full load bus voltage and the lowest motor starting voltage

b. Main Transformer

The rating should allow for the full generator operation, less the minimum sustained unit auxiliary loads. For conservative MVA rating, the rating is determined by using the maximum expected generator output, neglecting unit auxiliary loads. The transformer rated voltage should be selected considering the generator voltage control characteristics. A typical low voltage rating is 95-100% of the generator voltage rating, whereas typical high voltage rating is 100-105% of the rated voltage of the power.

c. Unit Auxiliary Transformers

The nominal optimized auxiliary bus loading capabilities, as a function of switchgear rating and the size of the largest motor on the bus should be calculated using load lists and % impedance of the UAT. As shown in Fig 1, for a multi-module power plant, the rating of UATs should be sized so that if one UAT fails, the other UAT can power both module power plant loads.

d. Medium Voltage Switchgears

The load carrying capability of the medium voltage switchgear bus is limited by the thermal rating of the unit auxiliary transformer and bus connections. However, once the thermal rating consideration is satisfied, the load carrying capability of the switchgear bus is primarily controlled by the switchgear interrupting and momentary ratings and/or by the impedance of the transformer winding supplying the bus. For a given switchgear rating, the impedance of the supply transformer determines the allowable bus loading.

Other parameters that can influence bus capability are the size of the largest motor connected to the bus, the type of bus load and the impedance and voltage variations of the high voltage supply to the transformer serving the bus.

e. Low Voltage Switchgear and MCC

When selecting distribution transformers, it is always best to review actual running and peak load readings instead of using the connected load as the basis for available capacity. If cooling fans are not installed, consider adding them if the increased rating and bus can handle the additional load.

The medium voltage switchgear energizes the low voltage switchgear through the distribution transformer. The load centers are fed from the low voltage switchgear, and they have connected loads such as large motors, heaters, and motor control centers.

f. DC and IP System

The DC system consists of several subsystems, safety related 125 VDC system, non-safety related 125 VDC system, and non-safety related 250 VDC system. This system also provides power to AC motor operated valves through DC/AC safety injection inverters.

The safety related 125 VDC system is an ungrounded class 1E, quality class Q, seismic category I system. The system consists of four independent subsystems (channels A, B, C and D), each corresponding to one of the four reactor protection instrumentation channels. There are two safety related DC subsystems per redundant safety related electrical division. Channels A&C correspond to division A, while channels B&D correspond to division B.

Non-Safety and Safety Related batteries shall be sized to supply power for 2 and 4 hour load cycles, respectively, in the event auxiliary power is interrupted concurrently with a loss of offsite power (LOOP). Exact battery backup time must comply with the result of safety analysis of reactor protection system.

Inverters are used to convert direct-current power to alternating-current power. They include auxiliary devices such as transfer switches, alternate source transformers and regulators, input rectifiers (other than battery chargers), and isolation devices (e.g., blocking diodes).

4.4 Electrical Protection System

Protection refers to the sense, command, and execute features with their associated interconnections (see IEEE Std 603-1991) that are provided to minimize equipment damage and any interruption of electrical service resulting from mechanical or electrical failures or other unacceptable conditions. The protection shall be capable of monitoring the connected preferred power supply and, where an alternate preferred supply is provided by the design of automatically initiating a transfer or alerting the operator to manually transfer to the alternate preferred power supply. Periodic testing to verify logic schemes and protective functions and periodic testing to verify set points are also the scope of functions of the electrical protection system.(See IEEE Std 741)[7]

While SMR has various advantages as mentioned earlier compared to existing large nuclear power plants, it is understood that its economic feasibility is inferior. Therefore, it is necessary to ensure the efficiency of SMR operation, and one of such measures is to integrate multiple units and operate remotely. To this end, it is very important to select an appropriate electrical protection and control system. Therefore, the implementation of the IEC 61850 standard along with the digital integrated protection relay is recommended for the electrical protection of SMR plant auxiliary power systems[8]. IEC 61850 provides benefits such as improved system reliability, reduced downtime, and easier maintenance[9]. It enables monitoring and control of the auxiliary power system from a central location, leading to better management of energy resources and improved operational efficiency. Additionally, offers several strengths and characteristics that make it an efficient and reliable protocol:

a. Standardization

IEC 61850 is an international standard that ensures interoperability among different vendors and equipment. This makes it easier to integrate various systems and devices, leading to increased efficiency and reduced costs.

b. Flexibility and Scalability

IEC 61850 allows for the configuration and customization of the communication system to meet specific needs. It can also accommodate new applications and functions without requiring major changes to the existing system. IEC 61850 can be used in small or large power systems, making it suitable for different sizes of substations.

c. High Performance and Cybersecurity

IEC 61850 is designed for high-speed data transfer, enabling real-time monitoring, control, and protection of the power system. IEC 61850 incorporates security features such as authentication, encryption, and access control to protect the power system from cyber-attacks.

d. Fault tolerance and Diagnosis

IEC 61850 uses redundant communication paths and devices to ensure high availability and reliability of the power system. IEC 61850 can provide detailed diagnostic information, allowing for proactive maintenance and problem resolution.

5. Conclusions

In recent years, a growing number of countries have adopted SMRs as part of their energy mix, influenced by climate change and carbon net zero policy. Currently, there is no separate codes and regulations for licensing of SMRs, so the licensing regulations applied to existing large nuclear power plants can only be applied. Therefore, it is urgent to establish a licensing regulations and criteria tailored to the characteristics of SMRs. Therefore, this paper proposes design criteria and design guidelines for the auxiliary power systems for SMR. Based on this, it is planned to develop more precise, safe, and efficient design criteria and guidelines in the future.

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