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# Configuration and Voltage Level Selection of Small Modular Reactor Auxiliary Power System

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## 1. Introduction

The SMR technology [1] is characterized by scaled down generation capacity from the conventional large capacity nuclear power plants. The size of the SMR module generator depends upon the turbine capacity. Additionally, the size of the largest single electrical loads like the reactor coolant pump (RCP) influence the medium voltage (MV) level selection. The configuration of the auxiliary power supply of a nuclear power plant is conventionally based on recommended industrial standards and regulations for nuclear power generating stations. Design of electrical systems must therefore conform to the approved standards and regulations in order to guarantee interoperability and safety which is a key concern in the nuclear industry. This paper proposes an SMR auxiliary power system configuration that is applicable to any generation capacity and performs design verification by software simulation using the electrical transient analyzer program (ETAP). The suitability of the proposed configuration and voltage selection is evaluated through load flow and short circuit current analysis.

## 2. SMR auxiliary power system configuration

### *2.1 Selection of standards and regulations*

The applicable standards and regulations function to ensure safety, compatibility, and consistency [2]. The industrial standards define different voltage levels for MV and low voltage (LV) switchgear and equipment. Conventional standards used are the institute of electrical and electronics engineers (IEEE) and international electro-technical commission (IEC) standards depending on the target market of the SMR being designed. Other special requirements for nuclear safety are given in the related codes and regulatory guides.

### *2.2 Voltage selection of major equipment*

This paper focused on the ANSI/IEEE standards that is popular in North America, Asia and parts of African continent where SMR technologies are highly applicable. The ANSI C84.1-2020, American National Standard for Electric Power Systems and Equipment-Voltage Rating (60 Hertz) [3] is used. The standard gives the nominal voltage ratings as; 4,160V, 6,900V and 13,800V for MV class, and 480V for the LV class but not limited to this range. ANSI standards are used for motors, generators, and other switchgear by specifying the capacity of the rotating device to be used according to the voltage level [4]. SMR configuration also complies with NEMA MG-1, which indicates the recommended capacity range for each voltage.

### *2.3 Design considerations for SMR auxiliary systems*

SMR's electrical systems are designed to have; redundancy, diversity, independence, and physical separation. The auxiliary power system is connected to the offsite power system at the switchyard through minimum two (2) preferred power supply (PPS) lines as required by the IEEE Std 765, that is the IEEE standard for preferred power supply for nuclear power generating stations [5].

### *2.4 Auxiliary power system configuration philosophy*

This section provides the description of the auxiliary power supply system of an SMR. The section describes the key features of the auxiliary power system with reference to approved standards and regulatory guidelines [6].

Three configurations were considered, and a trade-off analysis was performed to select an optimal configuration in this study. The analysis was based on technical and economic evaluation criteria. Technical evaluation criteria had higher weights allocated to the sub-criteria parameters for the analytical hierarchy process. The technical evaluation criteria used were: short circuit current analysis, least voltage drop, and least power losses. Fig. 1, Fig.2, and Fig.3 show the three configuration options evaluated in this study.

Fig. 1 shows a system configuration where two modules are installed on separate buses with each module having its own main transformer for switchyard connection. A provision has been made for the 13.8kV buses interconnection in the event of escalated power loss. Two unit auxiliary transformers are used at the 4.16kV voltage level conversion. Each UAT has been divided into two divisions. Each division has equipment which are redundant, independent, diverse and physical separated. This configuration leverages on the advantages of using three winding transformers. PPS 1 and PPS2 are of the same voltage level but are fed from independent sources through the switchyard. The merits and demerits of this configuration are shown in the trade-off analysis in the weights allocation at the analytical hierarchy computation.

Fig. 2 shows the second option of auxiliary power system configuration where two modules are installed on the same 13.8kV generator bus with one, two-winding main transformer for switchyard connection.

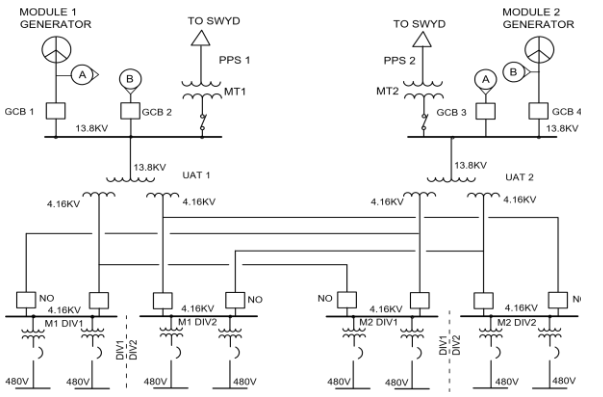


Fig. 1 SMR Auxiliary Power System Configuration Option 1

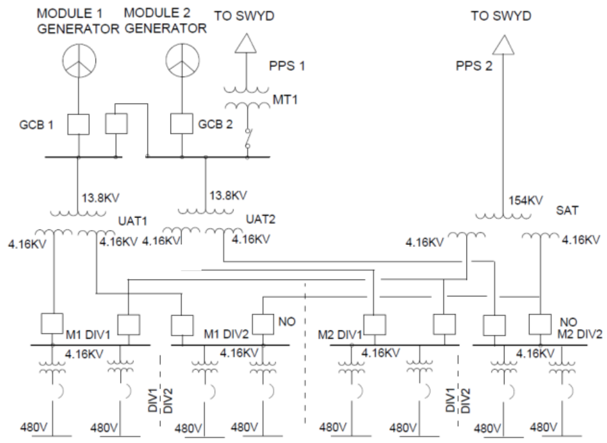


Fig. 2 SMR Auxiliary Power System Configuration Option 2

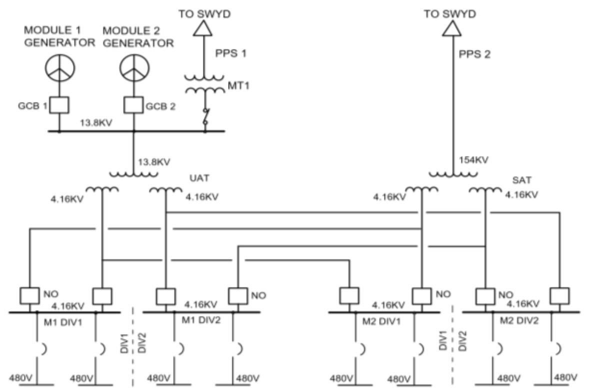


Fig. 3 SMR Auxiliary Power System Configuration Option 3

The MT route serves as the PPS 1 while PPS 2 provides power directly to the standby auxiliary transformer which is of lower power rating. Two UATs and one SAT are used at the 4.16kV voltage level conversion. The transformers have two divisions each with module specific equipment that are redundant, independent, diverse and physical separated. This configuration leverages on the advantages of using shared buses within a power plant. PPS 1 and PPS2 are of the same voltage level but are fed from independent sources through the switchyard. The merits and demerits of this configuration are shown in the trade-off analysis in the weights allocation at the analytical hierarchy computation

Fig. 3 shows the third option of auxiliary power system configuration. The layout is a combination style of Option 1 and Option 2. Both generators share the generator bus and main transformer in the same way as Option 2. The auxiliary power distribution system is the same as Option 1.

From the trade-off analysis report generated by the analytical hierarchy process software, Option 1 was selected. This section describes Option1 configuration of the auxiliary power system. Each module has two divisions fed from the UAT's secondary and tertiary winding respectively. Each UAT acts as a standby transformer to the other. Common loads for the plant are shared equally between the two unit auxiliary transformers. The normal power supply for the auxiliary power system (APS) is supplied through unit auxiliary transformers (UAT 1 and UAT 2) from module 1 and module 2 main generators. Alternatively, the unit auxiliary transformers can be energized from the transmission lines through the main transformers and switchyard buses which obtain supply from independent transmission lines.

The onsite power system consists of the alternating current (AC) power system, direct current (DC) power system, and instrumentation and control (I&C) power system. The AC power system has 5 main parts: The auxiliary transformers which convert the generated 13.8kV to redundant 4.16kV buses; 4.16kV to 480V step down transformers; 480V Class 1E and Non-class 1E load centers (LC) and 480V motor control centers (MCC); 480V emergency diesel generators (EDG); and alternate alternating current (AAC) source. Each of these subsystems have accessories for control and protection.

The APS provides a reliable power supply to the loads. Physical separation and electrical isolation are maintained between the power supplies to redundant equipment. Under normal operation, the APS receives power from both modules through the GCB1 and GCB2. During shutdown and start-up of the plant, the APS receives power from the second generator through the UAT. In the event of loss of offsite power, the power is supplied from the emergency diesel generator, and AAC in case the situation escalates by loss of EDG. The two (2) EDGs are located in physically separated and electrically independent from each other on the 480V safety buses. The EDGs are started when engineered safety features actuation (ESFA) signal occur, but without loss of offsite power (LOOP) are not connected to Class 1 E buses. The SMR class 1E loads are placed in the dc load centers.

In the event of ESFA signal with LOOP, initiation of a two-out-of-four loss of voltage or degraded voltage signal from the 480V Class 1E buses give automatic starting signal to the EDG. The normal feeder breakers and load breakers of the Class 1E bus are tripped except for the LC transformer feeder breaker. After EDG establish rated voltage, EDG is connected to the Class 1E bus.

*2.5 SMR auxiliary system configuration simulation*

The selected SMR configuration and choice of voltage levels was simulated using the electrical transient analyzer program (ETAP) using two generic modules each with an electrical capacity of 107MWe.

The sizing of transformers and switchgear and other major equipment was done using the generator capacities. The auxiliary loads were estimated based on the consideration that each module's auxiliary supply should not consume more than 5% of its total designed capacity. Transformers were designed with the consideration of 10% loading margins for future loads.

The RCPs were assumed to be the largest single unit loads in the system and were estimated to be 4 units per module. For this reason, they were placed under the 4.16kV buses. The loads are equally distributed in the buses to reduce the effects of fault currents on buses with major loads. Other shared loads like common buildings were assumed to be equality distributed between the modules. The auxiliary loads accounted for 4.63% of the installed capacity of 214MWe.The generator buses of 13.8kV were designed to be free from any loads but with redundant generator connections, each generator serving as back up to the other's auxiliary supply.

## 3. Results and discussion

Load flow analysis and short circuit interrupting current analysis was conducted using ETAP software for numerical analysis of the flow of electric power in the auxiliary power system. From this analysis, steady-state conditions of the designed electrical system are determined. The results from the three configuration options were used for trade-off analysis as technical evaluation criteria (TEC) using the analytic hierarchy process software (AHP) which represents a method for organizing and analyzing complex decisions, using mathematics and psychology [7]. Fig 4 shows the AHP parameters used in this study.

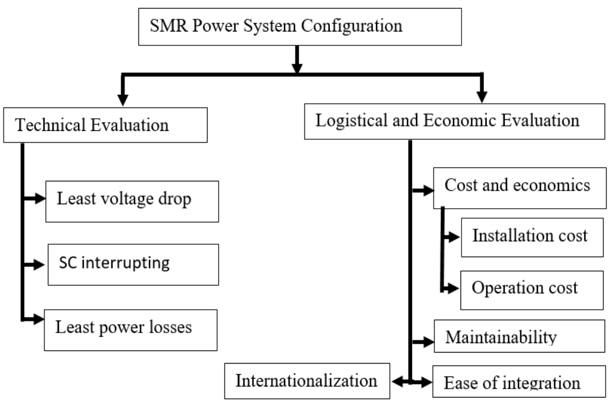


Fig. 4 AHP for Auxiliary power system configuration

The evaluated technical aspects were evaluated for the configuration options with the detailed safety buses (SR) and Non-safety buses (NS) as detailed below:

*3.1. Least voltage drop in the auxiliary power system buses*

This is desirable for optimal operation of the power plant. This will guarantee voltage stability and robust operations of the SMR. These best configuration should have the least voltage drop in every subsequent step of bus voltage levels. Table 1 shows the detailed results from the voltage drop evaluation in the three configuration options.

Table 1: Percentage bus voltage for different voltage levels per configuration

| Device | V kV | Config 1 | Config 2 | Config 3 | Config selected |
|---|---|---|---|---|---|
| | | Symm. kA rms | Symm. kA rms | Symm. kA rms | |
| M1 Gen bus | 13.8 | 100.00 | 100.00 | 100.00 | 1,2,3 |
| M2 Gen bus | | 98.77 | 98.77 | 98.31 | 2 |
| M1 NS DIVI | 4.16 | 98.77 | 98.75 | 98.31 | 1 |
| M1 NS DIVI | | 100.00 | 100.00 | 100.00 | 1,2,3 |
| M2 NS DIVI | | 98.79 | 98.74 | 98.39 | 1 |
| M2 NS DIVII | | 98.79 | 98.79 | 98.39 | 1 ,2 |
| M1 NS LV DivI | 0.48 | 97.15 | 97.1 | 96.74 | 1 |
| M2 NS LV DivI | | 97.19 | 97.21 | 96.74 | 2 |
| M1 NS LV DivII | | 97.15 | 97.15 | 96.74 | 1,2 |
| M2 NS LV DivII | | 97.21 | 97.18 | 96.74 | 1 |
| M1 SR LV DivI | | 97.63 | 97.11 | 97.22 | 1 |
| M2 SR LV DivI | | 97.20 | 97.21 | 96.74 | 2 |
| M1 SR LV DivII | | 97.63 | 97.63 | 97.22 | 1,2 |
| M2 SR LV DivII | | 97.21 | 97.18 | 96.74 | 1 |

*3.2 Least power losses.*

Power losses within the system is a significant phenomenon to be considered when it comes to choice of auxiliary system configuration. Least power losses is desirable for optimal performance and efficiency. Table 2 below, shows the detailed results from the power losses evaluation in the three configuration options.

Table 2: System losses for the three configuration options

| SYSTEM LOSS | OPTION 1 | OPTION 2 | OPTION 3 |
|---|---|---|---|
| Loss-MW | 0.425 | 0.0646 | 0.441 |
| Loss-Mvar | 15.866 | 0.62 | 15.977 |

*3.3. Short circuit interrupting current*

Short circuit interrupting current evaluation is an important phenomenon in switchgear selection. Lower values for interruption current at the buses signify better opportunities for installing cost effective switchgear. In this paper, three configuration options have been compared to identify the most appropriate option for lower interruption short circuit current consideration. Table 3 shows the detailed results from the short circuit interrupting current evaluation in the configurations.

Table 3: Short Circuit Interrupting Current for Various Configuration Options

| Device | V kV | Config 1 Symm. kA rms | Config 2 Symm. kA rms | Config 3 Symm. kA rms | Config selected |
|---|---|---|---|---|---|
| M1 Gen bus | 13.8 | 29.47 | 50.94 | 29.00 | 3 |
| M2 Gen bus | | 29.46 | 50.95 | 29.00 | 3 |
| M1 NS DIVI | 4.16 | 19.74 | 21.05 | 10.80 | 3 |
| M1 NS DIVI | | 19.68 | 21.00 | 10.77 | 3 |
| M2 NS DIVI | | 19.67 | 21.08 | 10.77 | 3 |
| M2 NS DIVII | | 19.71 | 21.07 | 10.80 | 3 |
| M1 NS LV DivI | 0.48 | 21.79 | 21.93 | 20.45 | 3 |
| M2 NS LV DivI | | 21.79 | 21.92 | 20.45 | 3 |
| M1 NS LV DivII | | 21.66 | 21.80 | 20.34 | 3 |
| M2 NS LV DivII | | 22.04 | 21.80 | 20.34 | 3 |
| M1 SR LV DivI | | 20.91 | 21.91 | 19.58 | 3 |
| M2 SR LV DivI | | 20.91 | 21.04 | 19.58 | 3 |
| M1 SR LV DivII | | 21.66 | 21.80 | 20.34 | 3 |
| M2 SR LV DivII | | 21.67 | 21.80 | 20.34 | 3 |

Table 4 shows the weighted scores of the criteria used and the preferred configuration for every criteria. The weights are ranked from 1 to 9 where 1 is of least importance and 9 is of high importance. All other applicable criteria's details for the three configuration options were estimated during the study.

Table 4: System losses for the three configuration options

| No | Criteria | Weighted score | Preferred configuration |
|---|---|---|---|
| 1 | Least voltage drop | 7 | Configuration 1 |
| 2 | Short circuit interrupting current | 9 | Configuration 3 |
| 3 | Least power losses | 8 | Configuration 2 |
| 4 | Cost and economics | 5 | Configuration 2 |
| 5 | Maintainability | 6 | Configuration 1 |
| 6 | Ease of integration | 5 | Configuration 1 |
| 7 | Internationalization | 2 | Configuration 1 |

The AHP results are as shown below;

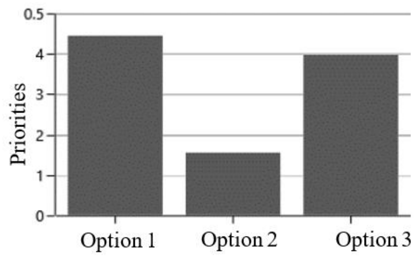


Fig. 5 AHP selection of Auxiliary System Configuration

Fig 5 shows the results of the configuration selection by the AHP. Configuration option 1 obtained the highest score in terms of priority while option 2 was the least preferred configuration.

Load flow analysis was conducted for the selected configuration (Option 1) as shown in table 5.

Table 5: Load flow analysis for configuration Option 1

| Bus ID | kV | % Mag. | Ang. | MW | Mvar | ID | MW | Mvar | Amp | %PF |
|---|---|---|---|---|---|---|---|---|---|---|
| Module1 Generator bus | 13.800 | 100.000 | 4.4 | 0.000 | 0.000 | 0.000 | 100.389 | 1.441 | 4200.4 | 100.0 |
| Module2 Generator bus | 13.800 | 100.000 | 4.4 | 0.000 | 0.000 | 0.000 | 100.103 | 1.426 | 4188.4 | 100.0 |
| Module1 Non-class 1E | 4.160 | 98.755 | 2.7 | 0.000 | 1.565 | 0.649 | 0.687 | 0.168 | 99.4 | 97.2 |
| Module1 Non-class 1E | 4.160 | 98.809 | 2.8 | 0.000 | 1.565 | 0.649 | 0.717 | 0.176 | 103.7 | 97.1 |
| Module2 Non-class 1E | 4.160 | 98.809 | 2.8 | 0.000 | 1.565 | 0.649 | 0.717 | 0.176 | 103.7 | 97.1 |
| Module2 Non-class 1E | 4.160 | 98.756 | 2.7 | 0.000 | 1.565 | 0.649 | 0.687 | 0.168 | 99.4 | 97.2 |
| Module1 Non-class LV | 0.480 | 97.170 | 0.4 | 0.000 | 0.711 | 0.144 | -0.711 | -0.144 | 898.4 | 98.0 |
| Module2 Non-class LV | 0.480 | 97.176 | 0.4 | 0.000 | 0.686 | 0.139 | -0.686 | -0.139 | 866.5 | 98.0 |
| Module1 Non-class LV | 0.480 | 97.170 | 0.4 | 0.000 | 0.711 | 0.144 | -0.711 | -0.144 | 898.4 | 98.0 |
| Module2 Non-class LV | 0.480 | 97.186 | 0.4 | 0.000 | 0.682 | 0.139 | -0.682 | -0.139 | 861.6 | 98.0 |
| Module1 Class 1E LV | 0.480 | 97.645 | 1.1 | 0.000 | 0.515 | 0.104 | -0.515 | -0.104 | 646.8 | 98.0 |
| Module2 Class 1E LV | 0.480 | 97.186 | 0.4 | 0.000 | 0.682 | 0.139 | -0.682 | -0.139 | 861.6 | 98.0 |
| Module1 Class 1E LV | 0.480 | 97.645 | 1.1 | 0.000 | 0.515 | 0.104 | -0.515 | -0.104 | 646.8 | 98.0 |
| Module2 Class 1E LV | 0.480 | 97.186 | 0.4 | 0.000 | 0.682 | 0.139 | -0.682 | -0.139 | 861.6 | 98.0 |

## 4. Conclusion

This paper adopts the use of SMR technology, multi-module model of two modules and an auxiliary power system 'Option 1 configuration'. The auxiliary power system voltage level was also selected using the ANSI C84.1-2020, standard for ease of integration and making the configuration easy to replicate for internationalization. The proposed SMR configuration and voltage selection criteria met its objectives. The configuration can be used for any capacity of SMR modules for up to the nth module summation since the configuration met the requirements for enhanced safety, defence-in-depth of electrical systems, lowered cost of auxiliary systems, and optimization electrical systems.

## Acknowledgement

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