Modelling and simulation of house load operation of HPR1000 NPP

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Abstract—In this paper, the house load operation of the unit is evaluated, taking the third-generation Nuclear Power Plant (NPP) HPR1000 as an example, considering the primary loop, the secondary loop and the entire on-site electrical power systems. The main work of this study is as following: Firstly, acceptance criteria and specific numerical requirements are set out; the simulation result should meet the relevant criteria. Secondly, the Simulink simulation model of the entire system is built in detail, which can be divided into primary loop, secondary loop and on-site electrical power system parts, with emphasis on the simulation modelling of the turbine generator unit. The component models of each part and their corresponding connection relationships of each part are shown and given. Finally, a house load operation simulation is performed, and the result is compared with the acceptance criteria to verify that whether the generator has the ability to transfer to house load operation as designed.

1. Introduction

HPR1000 is Chinese self-developed third-generation 3-loop pressurized water reactor, which has three trains of physically separated safety systems and a powerful combination of active and passive safety systems. The nominal electrical power output of HPR1000 NPP is 1180MW, depending on heat sink temperature.

This paper is intended to perform the house load operation study of the HPR1000 NPP, according to the requirements of IEC 62855:2016[1].

As the loss of off-site main power supply potentially affects many safety functions, the HPR1000 NPP is designed for load rejection on separation from the transmission lines, and for the subsequent reduction of the reactor output and the generator power output to levels sufficient to meet the needs of the disconnected plant for electrical power (the house load) without tripping the steam supply or tripping the turbo generator[2]. This plant transient occurs when grid instability or faults cause the high voltage breakers to trip, resulting in the on-site electrical power system loads being supplied by the main generator. House load of an NPP is intended to minimize progression from abnormal operation to faults. The transfer to house load operation will cause variations of the reactor core parameters, the voltage and frequency on the generator terminals and in the on-site electrical power systems. Therefore, this paper uses software simulation to model HPR1000 primary loop (i.e. the reactor core related loop), secondary loop (i.e. the turbine generator unit) and on-site electrical power system to evaluate the ability to transfer to house load operation of the unit, and comprehensively evaluate the transient process and its impact on the reactor core, the turbine generator and the on-site electrical power systems.
2. Acceptance criteria for house load operation

The acceptance criteria are defined to guide the following modelling and check the study. When the simulation meets the following acceptance criteria, it can be considered that the house load operation simulation is successful:

a) During the transition to house load, the generator speed should not exceed 1.1 times of the rated speed, and the generator will not be tripped by the relaying protection;

b) The steady-state operating frequency of the generator should be within 52Hz after the transition to house load;

c) The house load operation will not trigger AT (Auxiliary Transformer) to ST (Standby Transformer) transfer, i.e. the voltage of the 10kV normal power distribution system bus will not be lower than 0.7Un for a period longer than the setting value;

d) The house load operation will not trigger the Emergency Diesel Generator (EDG) to start, i.e. the voltage of the 10kV emergency power distribution system bus will not be lower than 0.8Un for a period longer than the setting value;

e) The reactor trip and turbine trip should not be initiated.

3. Model Description

3.1. Simplification of the Model

1) The transformer taps in the whole system do not change, always connected to the middle connector, and will not change during the fault.

2) The power loss of cables and other connecting wires in the plant power system are negligible.

3) The load under the low voltage bus (380V/690V) is equivalent to the centralized load. According to the load characteristics, each load is equivalent to the combination of motor load and static load. The power factor of the load is set to 0.85 (lagging) according to the actual engineering experience.

4) Both the reactive power compensation system and the reactive power limiting system of the generator are ignored. Only AVR system, under-excitation system and over-excitation system are used to regulate the generator terminal voltage.

5) The excitation saturation characteristic curve of the generator is equated with the fold line in Figure 1.

\[ \text{FIGURE 1 GENERATOR EXCITATION SATURATION CURVE} \]

3.2. NSSS model

The mathematical and physical models of the HPR1000 Nuclear Steam Supply System (NSSS) have been developed based on the fundamental mass, momentum and energy conservation laws and will be discussed as following. Based on these models, a dynamic simulation program of the HPR1000 NSSS has been developed in MATLAB/Simulink. The control systems implemented in the program includes the reactor power control system consisting of a G-banks control system and a R-bank control system, the pressurizer pressure and water level control system, the U-tube Steam Generator (UTSG) water level control system, the steam dump control and the Boron concentration control system\[3\].
The reactor dynamics is modelled using the point reactor dynamics equation. The fluid mechanics related model uses the mass conservation equation and the energy conservation equation. The pressurizer uses a three-region non-equilibrium model. In the three-region non-equilibrium model, the space inside the pressurizer is divided into surge water zone, main water zone and steam zone depending on the phase and enthalpy of the fluid in the pressurizer [4][5]. The coolant pump hydraulic calculations include hydraulic torque, pump head and pump heat. A detailed 15 lumps set total parameter kinetic model is used to apply moving boundaries for prediction of kinetic behaviour in the UTSG heat transfer zone.
3.3. Turbine model

The turbine generator set can be divided into four parts: synchronous generator, excitation system, PSS (Power System Stabilizer) system and speed control system. The connection relationship of each part is shown in Figure 3.

3.3.1. Excitation system

The excitation system includes the Automatic Voltage Regulator (AVR) system, the under-excitation limiting system, the over-excitation limiting system and the exciter of the turbine generator set.

1) AVR system modelling

The input of the AVR system is the generator terminal voltage, and the generator terminal voltage is maintained constant by adjusting and controlling the excitation current. The AVR system modelling refers to the standard AVR system in IEEE Type ST5B. Due to the access of the PSS system output $V_s$, the above-mentioned standard system has been appropriately modified. The modelling block diagram of the AVR system is shown in Figure 4.

2) Exciter system modelling

The output of the AVR system is used as the input of the exciter after the three-phase rectifier bridge. The $S_e$ ($V_e$) module and the $F_{ex}$ module use the AC1A standard system module in Simulink[6], and only the corresponding parameters are adjusted. Both of them are shown in Simulink in Figure 5. The parameter settings of the exciter are referred to those in IEEE Std 421.5-2005[7].

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**FIGURE 3 STRUCTURE DIAGRAM OF STEAM TURBINE GENERATOR UNIT**

**FIGURE 4 AVR SYSTEM IN SIMULINK**

**FIGURE 5 EXCITER SYSTEM IN SIMULINK**
3.3.2. PSS System
The PSS system applies the IEEE PSS2B standard system. The PSS system uses the active power deviation and the machine-side voltage deviation to compensate the negative damping of the excitation regulator by introducing additional signals in the excitation voltage regulator, so that the generator improves its ability to contain low-frequency system oscillations. The structure diagram of the PSSS system is shown in Figure 6. The parameter settings of the exciter are referred to those in IEEE Std 421.5-2005\(^7\).

3.3.3. Speed control system
The implementation of the speed control system in Simulink is shown in Figure 7, referring to the model presented in IEEE report\(^8\).

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**FIGURE 5 EXCITER SYSTEM IN SIMULINK**

**FIGURE 6 PSS2B STANDARD SYSTEM**

**FIGURE 7 SPEED CONTROL SYSTEM IN SIMULINK**
4. Simulation Studies

The house load operation is simulated using the visual simulation tool MATLAB/Simulink. Simulink is a block diagram environment for multi-domain simulation and model-based design, which supports system design, simulation, automatic code generation, and continuous testing and verification of embedded systems. It has the advantages of wide adaptability, clear structure and process, fine simulation, close to reality, high efficiency and flexibility. Based on the above advantages, Simulink has been widely used in complex simulation, design of control system and digital signal processing.

After the identification and screening of the operation conditions from the electrical power aspect of view, the typical case for the house load operation study is defined. The initial conditions before the house load operation are chosen as Reactor in Power (RP) and Small Break - Loss of Coolant Accident (SB-LOCA) respectively.

4.1. RP

The transferring to house load operation is triggered when the reactor is in power operation condition, which is a typical electrical loads configuration of the on-site electrical power system during the unit in normal operation. The simulation results are as follows.

a) During the transition to house load, the generator speed did not exceed 1.1 times of the rated speed, and the overspeed protection action was not triggered.

![Figure 8: Generator Rotor Speed During House Load Operation](image)

**Figure 8: Generator Rotor Speed During House Load Operation**

b) The steady-state operating frequency of the generator is within 52Hz (1.04 p.u.) after the transition to house load.

![Figure 9: Generator Frequency During House Load Operation](image)

**Figure 9: Generator Frequency During House Load Operation**

c) The voltage of the LG* 10kV normal power distribution system bus was not lower than 0.7Un for a period longer than the setting value, i.e. house load operation did not trigger AT (Auxiliary Transformer) / ST (Standby Transformer) transfer.
d) The voltage of the LH* 10kV emergency power distribution system bus was not lower than 0.8Un for a period longer than the setting value, and house load operation did not trigger the EDG to start.

4.2. SB-LOCA

The transferring to house load operation is triggered when a small break loss of coolant accident occurs in the unit, which is a typical electrical loads configuration of the on-site electrical power system during the unit in accident operation. The simulation results are as follows.

a) During the transition to house load operation, the generator speed did not exceed 1.1 times of the rated speed, and the overspeed protection action was not triggered.

b) The steady-state operating frequency of the generator is within 52Hz (1.04 p.u.) after the transition to house load.
c) The voltage of the LG* 10kV normal power distribution system bus was not lower than 0.7Un for a period longer than the setting value, i.e. house load operation did not trigger AT (Auxiliary Transformer) / ST (Standby Transformer) transfer.

![Figure 13: Generator Frequency During House Load Operation](image13)

**Figure 13 Generator Frequency During House Load Operation**

d) The voltage of the LH* 10kV emergency power distribution system bus was not lower than 0.8Un for a period longer than the setting value, and house load operation did not trigger the EDG to start.

![Figure 14: Voltage of 10kV Normal Power Distribution System Bus During House Load Operation](image14)

**Figure 14 Voltage of 10kV Normal Power Distribution System Bus During House Load Operation**

It should be stated that, during the house load operation, the reactor trip and turbine trip are not actuated when the plant is disconnected from the grid and operates at the house load. Thus, the HPR1000 NSSS control systems can accommodate the load rejection from 100%FP to house load transient successfully and maintain a sustained stable operation of the plant at the minimum house load.

5. Conclusion

This paper firstly introduces the brief information of HPR1000. Then a brief introduction to the modelling process of the primary loop model is made, and the model building process of the turbine
unit is introduced in detail, and the simulation analysis of house load during RP and SB-LOCA is carried out to demonstrate the house load capability of the HPR1000 unit.

From the above simulation results, the frequency of the system after house load does not exceed 52 Hz in both conditions, the generator protection is not triggered when the generator is disconnected from the grid, the AT/ST transfer is not triggered and the EDG is not started. Therefore, the HPR1000 NPP is able to transfer to house load operation as designed.

The house load study shows that the simulated system can successfully complete house load and maintain a steady state under the NPP’s auxiliary system loads.

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