Load Rejection Performance Analysis of HPR1000 NPP in the UK Grid

Qingliang Zhang *, Hui Sun, Changchun Zhai, Xiaowei Chen

(China Nuclear Power Engineering Co., Ltd. Shenzhen of Guangdong Prov. 518026, China)

zhangqingliang@cgnpc.com.cn *, sunhui@cgnpc.com.cn, zhaichangchun@cgnpc.com.cn, decxw@cgnpc.com.cn

Abstract—In this study, the full range of load rejection performance of HPR1000 NPP is evaluated against the UK Grid Code considering the primary loop, the secondary loop, and the electrical system. The main work of this paper includes three parts. Firstly, the UK grid operational requirements are introduced including frequency requirements, voltage requirements, power requirements, etc. The criteria and specific numerical requirements to be followed in the simulated steady-state and transient states are listed, and the simulation results should meet the grid operation requirements; Secondly, the Simulink simulation model of the whole system is built in detail, and the simulation model can be divided into NSSS, turbine generator, and electrical power system sections. The component modules of each part and their corresponding connection relationships of each part are shown and presented; Finally, a load rejection simulation is performed to demonstrate that the unit has the ability to regulate its active power output and frequency as required in the Grid Code.

1. Introduction

HPR1000 is Chinese self-developed Generation III nuclear power technology, which adopts an active and passive safety strategy to effectively enhance the ability to withstand nuclear safety risks. In terms of important nuclear safety parameters control, the three passive actions of HPR1000 are set in the three most important aspects of waste heat discharge, primary loop integrity, and complete shell stability, plus the traditional design of sub-critical and all the way water loading, all important aspects are guarded by both the active and passive, which greatly improves the safety of the nuclear power plant. If the unit is exported to the UK, one of the most important assessment is to verify its load rejection performance according to the UK Grid Code.

The use of radioactive substances must comply with relevant safety standards, and the nuclear power, as the largest radioactive energy source in use, puts safety at the forefront of both its nuclear island system and turbine generator sets[2].

This research is intended to develop the load rejection performance study of the Hua-long Pressurized Reactor (HPR1000) units, according to the requirements of UK Grid Code [1]. The load rejection is different from house load operation, which means the unit will transfer into an island grid operation powering some local loads.
2. Requirements and acceptance criteria for load Rejection

2.1 Overview of GB Grid Code

The 400 kV system voltage of the UK grid is normally kept within ±5% of the rated value. The minimum voltage can be 10% below the rated value and the maximum voltage can exceed the rated value by 10%. However, the voltage should not exceed the rated voltage by more than 15 minutes from +5% to +10% under normal conditions.

| NETS Nominal Voltage | Normal Operating Range | Time Period for Operation |
|----------------------|------------------------|---------------------------|
| 400 kV               | 400kV -10% to +5%      | Unlimited                 |
| 400 kV               | 400kV +5% to +10%      | 15 Minutes                |

2.2 Grid Frequency Requirements

In Limited Frequency Sensitive Mode-Overfrequency (LFSM-O), each power generation module shall be capable of reducing active power output in response to the frequency on the total system when this rises above 50.4Hz.

In Frequency Sensitive Mode (FSM), the frequency control device must be capable of being set so that it operates with an overall speed droop of between 3% and 5%. The power generation module should be able to provide active power frequency response in accordance with the associated requirements. For the power generation module with inertia, the delay of initial active power frequency response should not be greater than 2 seconds. The detailed requirement is recorded in ECC.6.3.7 of the Grid Code.

2.3 Load Rejection Requirements

The Load Rejection study should be carried out to demonstrate the capability of transferring into an island grid of the power generation module at emergency scenarios as required in Grid Code.

The load rejection simulation is carried out based on the requirements set out in ECP.A.3.6.2 where a specific diagram (as shown in Figure 1) is provided for the setup and simulation procedure of Load Rejection. Accordingly, the simulation study model is set up with the power generation module connected to the total system and connected with a local load shown as “X”. The local load “X” is set to a minimum for which the power generation module can control the power island frequency to less than 52Hz. The frequency may transiently exceed 52Hz, but the time beyond 52Hz should be less than the high frequency protection trip time for the power generation module.
2.4 Acceptance Criteria

The purpose of the load rejection study is to demonstrate that the power generating module can control the frequency of the isolated system below 52Hz unless this causes the power generation module to operate below its minimum regulating level.

As frequency response, the active power output of the power generation module and the reactor should fulfil the following requirements:

a) Both under LFSM-O and FSM, the power generation module should control the frequency of the isolated system below 52Hz unless this causes the power generation module to operate below its minimum regulating level; and

b) Both under LFSM-O and FSM, the reactor trip and turbine trip should not be triggered during the load rejection transient.

3. Model Description

3.1 Simplification of the Model

a) The transformer taps in electrical system remain stable connecting to the middle connector, and will not be changed during the fault;

b) The power loss of cables and other connecting device in the power system are negligible and omitted;

c) The low voltage loads of the same bus are equivalent to a 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;

d) The reactive power limiting system of the generator are ignored. Only Automatic voltage regulator (AVR) system, under-excitation system, and over-excitation system are used to regulate the generator terminal voltage; and

e) The excitation saturation characteristic curve of the generator is considered in the simulation according to the manufacturer’s information.
3.2 NSSS model
The primary loop performance should also be assessed together with the secondary loop, and electrical system. The 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 summarized as follows. 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-banks control system, the pressurizer pressure and water level control system, the UTSG water level control system, the steam dump control and the boron concentration control system[4].

The point reactor dynamics equation is used to represent the reactor dynamics. 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 [5][6]. 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 behavior 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 2.

![Figure 2 Structure Diagram of Steam Turbine Generator Unit](image)

3.4 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.

- AVR system modeling
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 modeling refers to the standard AVR system in IEEE Type ST5B. Due to the access of the PSS system output Vs, the above-mentioned standard system has been appropriately modified. The modeling block diagram of the AVR system is shown in Figure 3.
Exciter system modeling
A three-phase rectifier bridge deals with the output of the AVR system, and the result will be used as the input of the exciter. The AC1A standard system module in Simulink\(^9\) is used to represent Se (Ve) module and the Fex module. Only some corresponding parameters are adjusted. Both of them are shown in Simulink in Figure 4. The parameter settings of the exciter are referred to those in IEEE Std 421.5-2005.

3.5 PSS System
PSS system applies IEEE PSS2B standard system. The PSS system uses the deviation of the active power and the terminal voltage to compensate for the negative damping of the excitation regulator by introducing additional signals into the excitation voltage regulator, so that the generator can effectively improve the ability to contain the system low-frequency oscillation. The structure diagram of the PSS system is shown in Figure 5.
3.6 Speed control system

The implementation of the speed control system in Simulink is shown in Figure 6.

4. Simulation Studies

4.1 FSM

The simulation is set up with the power generation module operating under FSM, in which case the power generation module changes its active power output in response to the change in system frequency without any inherent dead band. The power generation module is set to an initial condition of operating at its maximum lagging power factor and outputting maximum of its rated active power capacity.

During the Load Rejection, the power generation module is islanded from the grid but is still supplying a local load \((X)\) of 673MW and its auxiliary system loads. The total demand within the islanded system is higher than the power generation module’s minimum operating level which is assumed to be 55% of the registered capacity. The simulated frequency variation is shown in Figure 7. The generator active power output and turbine power output are shown in Figure 8 and Figure 9. It demonstrates that, when the power generation module is disconnected from the grid, it is capable to control the frequency of the islanded system to below 52Hz.

It is noted that the frequency exceeds 52Hz for a duration less than 4 seconds, which is less than the high frequency protection trip time for the power generation module, when the power generation module is set to operate in FSM.
4.2 LFSM-O

The simulation is set up with the power generation module operating under LFSM-O in which case the power generation module will respond to system frequency only when it rises above 50.4Hz. The power generation module is set to an initial condition of operating at its maximum lagging power factor and outputting maximum of its rated active power capacity.

During the Load Rejection, the power generation module is islanded from the grid but is still supplying a local load (X) of 660MW and its auxiliary system loads. The total demand within the islanded system is higher than the power generation module’s minimum operating level which is assumed to be 55% of the registered capacity. The simulated frequency variation is shown in Figure 10. The generator active power output and the turbine power output are shown in Figure 11 and Figure 12. Compared to operating under FSM, a slightly higher transient overfrequency is observed due to the defined dead band of frequency response under LFSM-O. Nevertheless, the simulation results demonstrate that the power generation module operating under LFSM-O is capable of controlling the frequency of the islanded system to below 52Hz.
It is noted that the frequency within the islanded system exceeds 52 Hz for a duration less than 4 seconds, which is less than the high frequency protection trip time for the power generation module, when the power generation module is set to operate in LFSM-O.

5. Conclusions
This paper firstly introduces the issue of load rejection when the unit is connected with the UK grid, which is a special interest different with Chinese grid. Then a brief introduction to the modeling of the primary loop is made, the model building process of the turbine unit is introduced in detail, and the simulation analysis of load rejection under FSM mode and FSM-O mode is carried out to assess the capability of the HPR1000.

From the above simulation results, the frequency of the system after load rejection does not exceed 52 Hz in either FSM or LFSM-O mode, and the generator protection is not triggered when the generator is disconnected from the main grid. The reactor trip is not triggered, either. Therefore, the unit is able to complete the load rejection according to the requirements of the Grid Code.
The load rejection study shows that the simulated system can successfully complete load rejection and maintain a steady state under a certain local load and its auxiliary system load. The simulation results prove the frequency control performance of the plant.

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