Modeling and Simulation of Fault Ride Through Performance of HPR1000 NPP in the UK Grid

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Abstract—This study focuses on the fault ride through capability of HPR1000 NPP in the UK grid and presents a Simulink-based modelling and simulation of the demonstration. The paper firstly introduces the fault ride through requirements of the UK grid, then describes the modelling process and analyses the simplified part accordingly, and finally analyses a three-phase ground fault with a duration of 140ms and a three-phase ground fault with a residual voltage of 85% and a duration of 180 seconds. The results show that the fluctuations of the plant under various fault ride through scenarios meet the requirements of the UK grid indicating the plant has fault ride through capability in the UK grid.

1. Introduction

Based on more than 30 years of experience in nuclear power research, design, construction, and operation, Hua-long Pressurized Reactor (HPR1000) nuclear power plant (NPP) is developed as an advanced megawatt-class Pressurized Water Reactor (PWR) nuclear power technology considering the feedback from Fukushima nuclear accident and the latest Chinese and global safety requirements. As the main brand of Chinese nuclear power industry, HPR1000 is designed with a safety design concept that combines active and passive safety technologies[1]. The reactor core with 177 fuel assemblies, multiple redundant safety systems, single reactor arrangement, double-layered containment, a comprehensive and balanced implementation of the "defense in depth" design principle, and comprehensive serious accident prevention and mitigation measures, its safety indicators and technical performance have reached the advanced level of international third-generation nuclear power technology, with complete independent intellectual property rights.

Since 2006, the UK has gradually increased its support for nuclear power[2]. In October 2015, China and the UK signed an agreement to cooperate in the construction of a new NPP in Bravel B. During the Generic Design Assessment process, the ability of the units to operate safely and stably in the UK grid has become a primary concern for all parties[3][4]. This paper focuses on the Fault Ride Through (FRT) capability of the HPR1000 in the UK grid, based on a Simulink model.

2. Grid Code Requirements

There are two main types of FRT requirements for NPP to demonstrate, the first one is the FRT specification requirement with a maximum duration of 140ms and the second one is the FRT specification requirement with a duration of more than 140ms.
2.1 Faults with a Duration up to 140ms
The power generation module is required to remain connected and be stable for any balanced and unbalanced fault where the voltage at the grid entry point remains on or above the heavy black line shown in the Figure 1 below.

![Figure 1 FRT Requirements (Duration up to 140ms)](image)

The acceptance criteria is shown as follows.

a) The power generation module shall be capable of satisfying the requirements when operating at rated power output with the maximum lagging power factor;

b) The pre-fault voltage shall be set as 1.0p.u. and the post fault voltage shall not be less than 0.9p.u.;

c) The protection schemes and settings should not jeopardise FRT performance; and

d) The power generation module shall be designed such that upon the clearance of the fault on the transmission system and within 0.5s of restoration of the voltage at the grid entry point to 90% of nominal voltage or greater, the active power output shall be restored to at least 90% of the level immediately before the fault. Once active power has been restored to the required level, active power oscillations shall be acceptable that the oscillations are adequately damped and the total active energy delivered during the period of the oscillations is at least that which would have been delivered if the active power was constant.

2.2 Faults with a Duration more than 140ms
For the faults and voltage disturbances on the transmission system causing voltage dips with a duration greater than 140ms, power generation module must remain transiently stable and connected to the system. The voltage at the grid entry point should be on or above the heavy black line shown in the Figure 2 below.
The acceptance criteria is shown as follows.

a) The power generation module should provide active power during the voltage dips at least in proportion to the retained balanced voltage at the grid entry point and shall generate maximum reactive current;

b) The power generation module should restore active power immediately to at least 90% of the level before the occurrence of the dip within 1s after the restoration of the grid entry point voltage to 1.0p.u. Once active power has been restored to the required level, active power oscillations shall be acceptable that the oscillations are adequately damped and the total active energy delivered during the period of the oscillations is at least that which would have been delivered if the active power was constant.

3. System Model

3.1 Assumptions

a) The taps of the transformers in the whole system remain unchanged. The taps of the transformers are always connected in the middle position, and the taps will not be adjusted due to faults;

b) The power loss of the cables and other connecting device in power system is negligible. The rated capacity of the power generation module is 1320MVA, and the line loss is small and can be ignored;

c) The loads under the same low-voltage bus are equivalent as a concentrated load. According to the load characteristics, each load is equivalent to a combination of motor load and static load. Based on practical experience, the load power factor is set to 0.85 (lagging);

d) The power generation module’s reactive power limit is ignored. Only use Automatic voltage regulator (AVR) system, under-excitation system and over-excitation system to adjust power generation module’s voltage; and

e) The excitation saturation characteristic curve of the power generation module is approximately replaced by a typical model.

3.2 NSSS Model

The mathematical and physical models of the HPR1000 Nuclear Steam Supply System (NSSS) have been developed based on the fundamental laws of neutron dynamics and conservations of mass, momentum and energy. Those models, consisting of a point reactor kinetics model, a hydrodynamic
volume model, a heat structure model, a pressurizer model, a reactor coolant pump model, and a UTSG model, are described as follows.

a) Reactor dynamics\cite{5} are modelled using the point reactor kinetics equations, which are derived from transport and diffusion theory. The reactivity feedback effects due to fuel and coolant temperature changes have been considered;

b) The dynamic model of a hydrodynamic volume has been developed by applying the mass, momentum and energy conservation equations to a control volume of fluid with no work and constant volume. It can be used to describe hydrodynamic and thermodynamic characteristics of fluid in a control volume including those of coolant in the reactor core, in the RCS tubes and chambers, in the secondary side feedwater and the steam channels of UTSG, etc.;

c) Heat structures represent the solid structures bounding hydrodynamic volumes (i.e., pipe walls) or structures internal to the volumes (fuel pins). The modelling capabilities of heat structures are general and include fuel pins or plates with nuclear or electrical heating, heat transfer across steam generator tubes, and heat transfer from pipe and vessel walls. In the mathematical modelling of heat structures like those, the heat conduction along the axial direction can be neglected. Thus, by dividing a heat structure into several nodes along the radial direction, one-dimensional heat conduction can be used to compute the temperature distribution within the heat structure;

d) The pressurizer plays an important role in controlling the reactor coolant system pressure during in-surge or out-surge transients of a pressurized water reactor (PWR) NPP. Among various types of pressurizer models, the widely-used three-region non-equilibrium model\cite{6} has been adopted in the present study. It divides the space in a pressurizer into a surge water region, a main water region, and a steam region according to different phases and enthalpies of the fluid in the pressurizer. For each region, the basic conservation laws of mass and energy are employed to develop dynamic equations describing thermodynamic behaviors of steam and water;

e) The Reactor Coolant Pump hydraulic calculations include the calculations for the hydraulic torque, pump head, and pump heat. The RCP hydraulic torque and pump head are calculated from user supplied pump homologous curves; and
The steam generator serves as the major heat sink in a PWR plant to transfer the heat generated in the reactor core to the circulating water in the secondary side of UTSG generating high pressure steam to produce power. The steam generator of HPR1000 NPP is a vertical-shell U-tube evaporator with integral moisture separating equipment and natural circulation flow in the secondary side. Because of the two different heat transfer mechanisms between the tube wall and the secondary fluid, a dynamic UTSG model with the primary side coolant, tube wall and secondary side fluid divided into 15 lumps has been adopted here. A dynamic boundary is employed in the model to divide the effective secondary heat exchange region (tube bundle region) into a subcooled heat transfer region and a boiling heat transfer region.
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 include the reactor power control system consisting of a grey rods control system and a R rods 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. The overview of the NSSS model is shown in Figure 3.

3.3 Steam 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 4.

**Excitation system**
The excitation system includes the 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 $V_s$, the above-mentioned standard system has been appropriately modified. The modeling block diagram of the AVR system is shown in Figure 5.

![Figure 4 Structure Diagram of Steam Turbine Generator](image)

**Figure 4 Structure Diagram of Steam Turbine Generator**

![Figure 5 AVR System Modeling Block Diagram](image)

**Figure 5 AVR System Modeling Block Diagram**
Modeling of exciter system
The output of the AVR system is used as the input of the exciter after the three-phase rectifier bridge. The block diagram of the exciter is shown in Figure 6. The Se (Ve) module and the Fex module use the AC1A standard system module in Simulink, and only adjust the corresponding parameters. The parameter setting of the exciter refers to the parameter setting in IEEE Std 421.5-2005.

\[ V_{i\text{Fmax}} - K_o I_{\text{ID}} \]
\[ \frac{1}{K_c + s_T(V_c)} \]
\[ V_{\text{Eem}} \]
\[ V_{\text{E}} \]
\[ I_{\text{Fex}} \]
\[ V_{\text{E} \text{in}} \]
\[ V_{\text{E}} \]
\[ I_{\text{ID}} \]

**FIGURE 6 BLOCK DIAGRAM OF EXCITER SYSTEM**

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 7.

**FIGURE 7 PSS2B STANDARD SYSTEM**

Speed control system
The implementation of the speed control system is shown in Figure 8, referring to the model presented in IEEE report.
4. Acceptance guidelines
According to the requirements in the Grid Code, the fault ride through performance has the following requirements.

a) The voltage at the grid entry point shall be maintained above the thick black line as defined in chapter II;

b) The active power output of the generator shall be restored to at least 90% of the pre-fault level within 0.5 or 1.0 seconds after the voltage at the grid entry point has been restored; and

c) For a sudden voltage drop due to a three-phase short-circuit fault on the transmission system or any asymmetrical short-circuit fault, the generator shall be required to maintain transient stability and disconnect from the transmission system.

5. Simulation Studies
The FRT study is done using Simulink, a visual simulation tool in Matlab. Simulink is a modular graph environment for multi-domain simulation as well as model-based design. It supports system design, simulation, automatic code generation, and continuous testing and verification of embedded systems. Simulink provides graphical editors, customizable module libraries, and solvers that enable dynamic system modeling and simulation. Simulink has the advantages of wide adaptation, clear structure and flow, fine-grained simulation, closeness to reality, high efficiency, and flexibility. Based on these advantages Simulink has been widely used for complex simulation, the design of control theory, and digital signal processing.

According to the requirements in Grid Code, the FRT demonstrations can be divided into the following two sections:

a) Section 2.1 defines the requirements for symmetrical and asymmetrical transmission system faults with a duration limit of 140ms; and

b) Section 2.2 defines the requirements for symmetrical faults and disturbances exceeding 140ms.

5.1 Three-phase ground fault with a duration of 140ms
The example in this section is a three-phase ground fault with a duration of 140ms at a 400kV grid connection. The simulation results are as follows.

According to the simulation results and assessment, the primary loop can operate smoothly during the fault, and the reactor trip is not triggered.

As shown in Figure 9, the generator terminal voltage can be restored to 1p.u. after the fault. The voltage at the generator's parallel network is always above the reference curve, which is in accordance with the requirements in Grid Code.

It can be derived from Figure 10 and Figure 11 that the active and reactive power output of the generator can be restored to the pre-fault level. The active power output of the generator is restored to more than 90% of the pre-fault level within 0.5 seconds after the voltage is restored, which is in accordance with the requirements of the Grid Code. As shown in Figure 12, the generator input mechanical power is reduced to about 0.82 p.u. during the fault. After the fault it can be restored to the pre-fault level.
**FIGURE 9** Generator parallel network voltage and generator terminal voltage

**FIGURE 10** FRT generator active power

**FIGURE 11** FRT generator reactive power

**FIGURE 12** FRT generator input mechanical power
5.2 Three-phase ground fault with residual voltage of 85% for 180 seconds

The example described in this section sets up a three-phase ground fault with a residual voltage of 85% and a duration of 180 seconds at a 400 kV grid parallel network. The simulation results are as follows.

According to the simulation results and assessment, the primary loop can operate smoothly during the fault, and the reactor trip is not triggered.

As shown in Figure 13, the generator terminal voltage can be restored to 1 p.u. after the fault. The voltage at the generator's parallel network is always above the reference curve, which is in accordance with the requirements in Grid Code.

It can be derived from Figure 14 and Figure 15 that the active and reactive power output of the generator can be restored to the pre-fault level within a period of time. The active power output of the generator is restored to more than 90% of the pre-fault level within 0.5 seconds after the voltage is restored, which is in accordance with the requirements in the Grid Code.

As shown in Figure 16, the generator input mechanical power is reduced to about 0.5 p.u. during the fault. After the fault it can be restored to the pre-fault level.
6. Conclusions
In this paper, the NSSS, the steam turbine system, and the electrical system of the HPR1000 is simplified, modeled and parameterized with reference to the international common generator set combined with the actual condition. The HPR1000 is fault tested with reference to the Grid Code. The simulation results of a three-phase ground fault with a duration of 140 ms and a three-phase ground fault with a residual voltage of 85% and a duration of 180 s show that the HPR1000 synchronous generator set meet the Grid Code requirements and is capable of performing FRT. This can underpin the grid firmly and also keep the stable operation of the plant during FRT scenario.

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