3D SIMULATION OF CANDU REACTOR REGULATING SYSTEM

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ABSTRACT

Present paper shows the evaluation of the performance of the 3-D modal synthesis based reactor kinetic model in a closed-loop environment in a MATLAB/SIMULINK based Reactor Regulating System (RRS) simulation platform. A notable advantage of the 3-D model is the level of details that it can reveal as compared to the coupled point kinetic model. Using the developed RRS simulation platform, the reactor internal behaviours can be revealed during load-following tests. The test results are also benchmarked against measurements from an existing (CANDU) power plant. It can be concluded that the 3-D reactor model produces more realistic view of the core neutron flux distribution, which is closer to the real plant measurements than that from a coupled point kinetic model. It is also shown that, through a vectorization process, the computational load of the 3-D model is comparable with that of the 14-zone coupled point kinetic model. Furthermore, the developed Graphical User Interface (GUI) software package for RRS implementation represents a user friendly and independent application environment for education training and industrial utilizations.

Key words: Reactor Regulating System, Graphical User Interface, Matlab

Introduction

The reactor regulating system, as a part of the overall plant control system, directly controls the reactor power, and sets it either to an operator-allocated power set point (Alternate Mode) or to the power level required to maintain certain steam pressure in the steam generator (Normal Mode) [1]. Specifically, it includes input sensors, a collection of Digital Control Computer (DCC) programs, reactivity control devices and the related control logicsis, represented in **Figure 1**.

The main functions of the RRS are to:
1. Automatically control the reactor bulk power to the power set point between 10-6 FPU and 1.0 FPU at a controlled rate. This is called bulk (global) control.
2. Maintain the neutron flux distribution close to its nominal design shape, so that the reactor can be operated at the full power without violating channel and bundle power limits. This indicates the spatial (differential) control.
3. Insert or withdraw reactivity devices at a controlled rate to maintain reactivity balance in the core. These reactivity devices compensate for the reactivity change due to variations in Xenon concentration, fuel burn-up, moderator poison concentration, and refueling effects, etc.
4. Monitor some important plant parameters and reduce power quickly when any parameter exceeds the limit. Parameter limits may be specified for economic or safety-related issues.

5. Withdraw shutoff rods automatically when the trip channels have been reset following a reactor trip on SDS1.

Furthermore, as a safety-related system, the RRS also meets the requirements for preventing loss of regulation (LOR). The frequency of LOR must be as low as possible. The RRS also is required to prevent LOR on any seismic event of intensity up to design basis earthquake (DBE) intensity. The reliability of the RRS is also very important. However, the RRS is not required to be functional under conditions associated with a Loss-of-Coolant Accident (LOCA), such as high temperature, humidity or radiation.

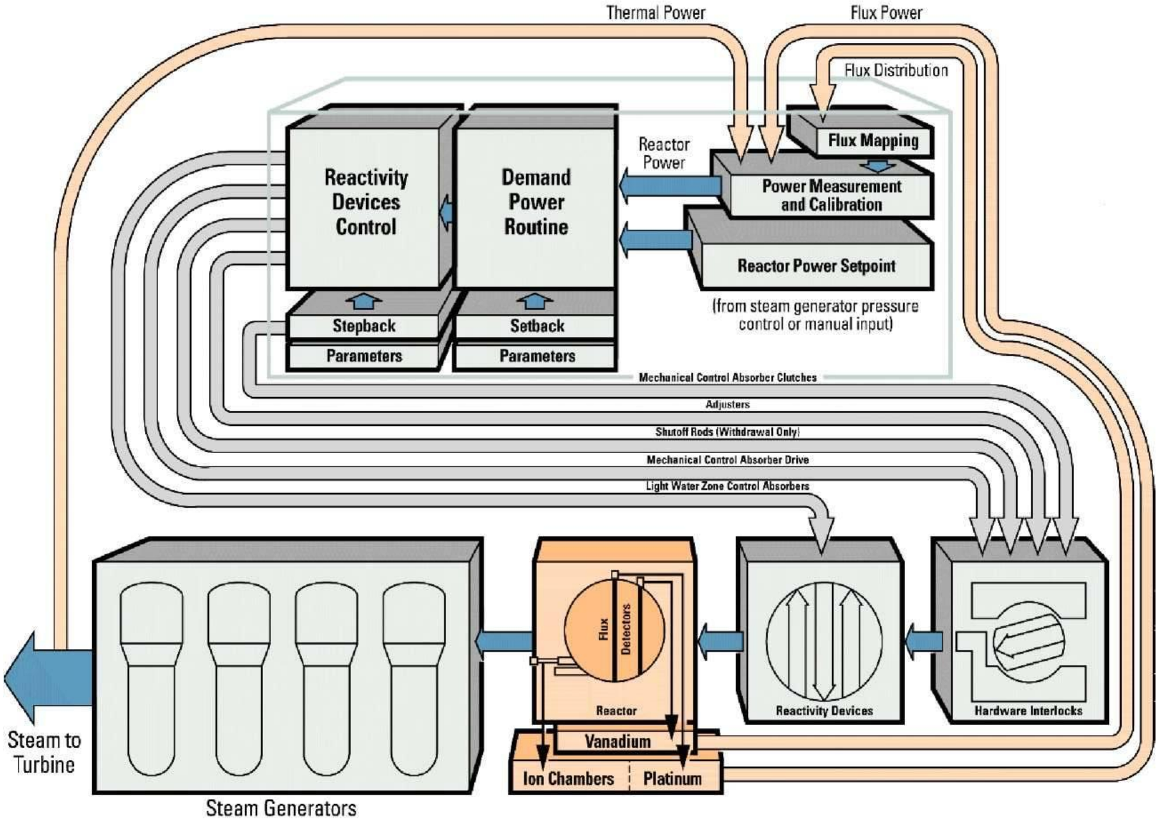


Figure 1 *CANDU RRS block modules [2]*

MATLAB/SIMULINK simulation platform of the RRS

MATLAB/SIMULINK software environment has facilitated the simulation of the CANDU RRS. Since our research mainly focuses on the reactor power short-time regulating, a simplified block diagram of the CANDU RRS, which contains the most functional routines and control algorithms, is represented in **Figure 2**.

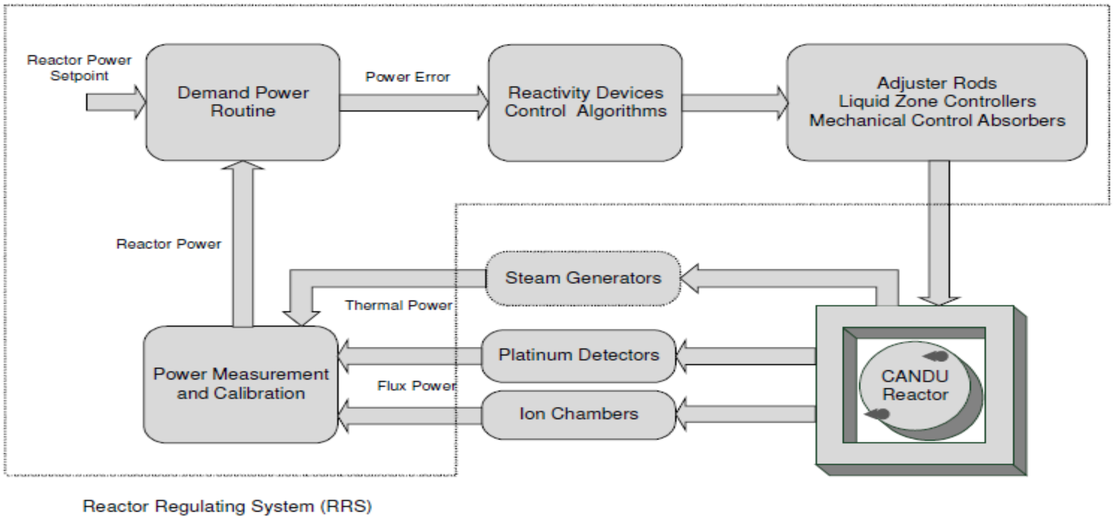


Figure 2 *Block diagram of RRS in CANDU reactors*

Matrix and vector representation

MATLAB/SIMULINK software provides a convenient environment to perform the matrix operations, such that the entire RRS system can be simulated in a matrix form. The idea is to decompose every module/routine of the RRS, express all the principles by mathematic equations, and write the equations to the criteria matrix form. Then the software chooses the appropriate synthetic internal functions from the SIMULINK library to develop each block, which represents the mathematic model of the RRS' module, and finally connects all the blocks, compiles them and performs simulations. A necessary procedure before the simulation is that the initialization of all the parameters involved in the simulation is required. For dynamic simulations, steady-state authorization also needs to be assessed.

It has been established that the basic functions of the RRS are to maintain reactor power and rate of change in power at specified setpoints (bulk control), and to maintain the reactor power distribution shape close to its nominal design shape (spatial control); the use of stable feedback controls based on neutron flux accomplishes these functions. Figure 3 shows a block diagram of the flux control loop for bulk power control.

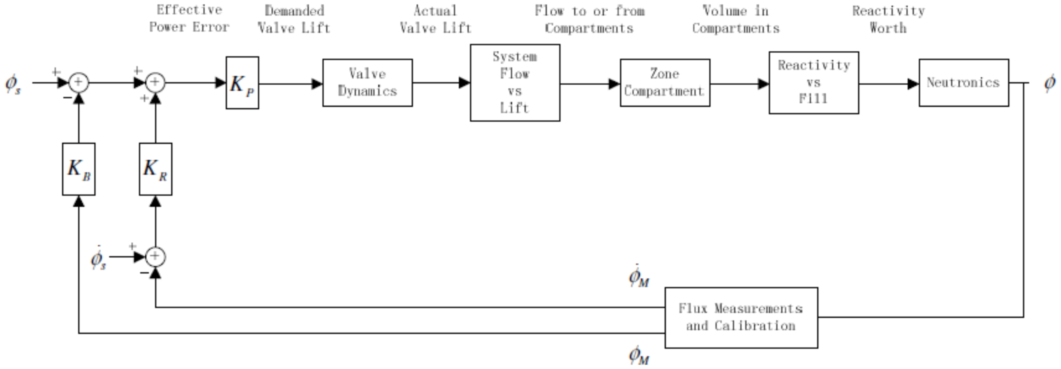


Figure 3 *Block diagram of a flux bulk control loop*

Efficient implementation of the RRS simulation platform

A CANDU RRS simulation platform established by MATLAB/SIMULINK is illustrated in **Figure 4**. As shown, main control routines and devices are simulated, including reactor neutron and thermal power measurement and calibration, demand power and power error calculation, control algorithms and mechanical characteristics of liquid zone controllers, adjuster rods and mechanical control absorbers, and the reactor dynamic system.

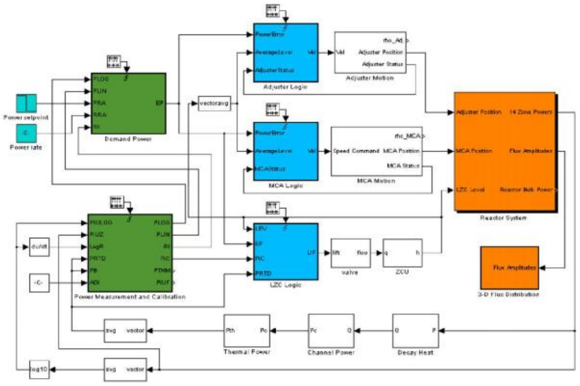


Figure 4 *MATLAB/SIMULINK simulation platform for the CANDU (RRS)*

Simulations of power manoeuvring operations

In this study, power maneuvering test scenarios have been simulated. The reactor power setpoint is reduced gradually from 1.0 FPU to 0.9 FPU at a rate of 0.1 FPU/s. The reactor bulk power control under this command is illustrated in Figure 5. For comparison purposes, the response from the coupled point kinetic model is also included. As far as the bulk power is concerned, the simulation results show clearly that both models can achieve the load following requirements successfully. The local enlargements of Figure 5 illustrate that both the overshoot and the steady-state error of the modal synthesis model are close to those of the coupled point kinetic model. However, both the overshoot and steady-state error of the modal synthesis model are relatively smaller than those of the coupled point kinetic model.

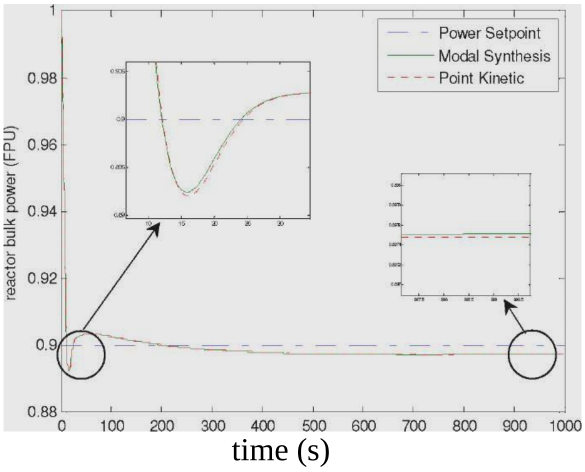


Figure 5 *Bulk power responses based on coupled point kinetic and modal synthesis models (the reactor power is reduced from 1.0 FPU to 0.9 FPU at 0.1FPU/s)*

Figure 6 illustrates the simulation of reactor zonal power responses under the same power maneuvering condition. The 14 curves represent normalized power dynamics within 14 zones. Therefore, it is observed that powers in 14 zones are almost regulated to the level of bulk power. Basically, the requirement of the spatial control is met, while the power distribution shape is somewhat maintained. From **Figure 5** and **Figure 6**, it can be concluded that reactor modal modeling implemented within the RRS simulation platform can meet the requirement of power transient simulation and analysis.

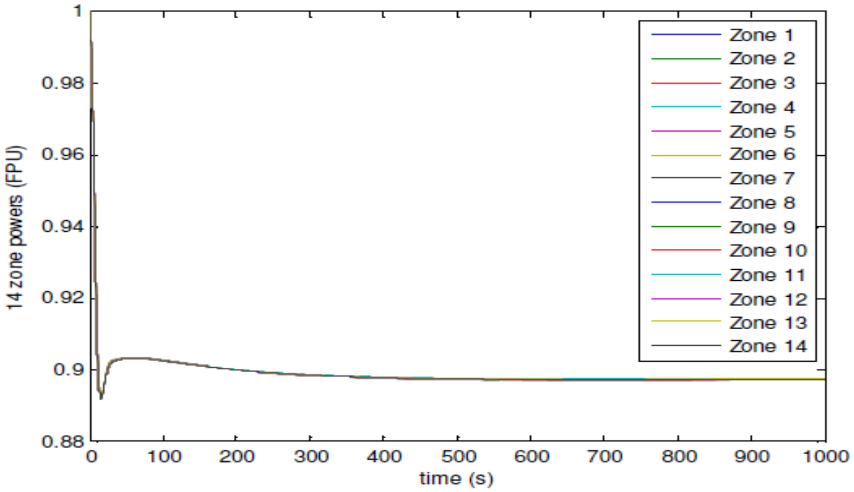


Figure 6 *Simulation result of reactor power spatial control (1.0 FPU - 0.9 FPU, at a rate of 1%FP/second)*

For comparison purposes, **Figure 7** illustrates the simulation of four power transients at different rates of power maneuvering. The range of power reduction is kept the same, i.e. 1.0 FPU to 0.9 FPU. However, the rates are respectively 1.0% FP/second, 0.5% FP/second, 0.25% FP/second, and 0.1% FP/second, which correspond to power-reducing times of 10 seconds, 20 seconds, 40 seconds and 100 seconds. **Figure 7** illustrates reactor bulk power following results. It can be observed that a smaller power reduction rate, there is a reduction in the overshoot power response.

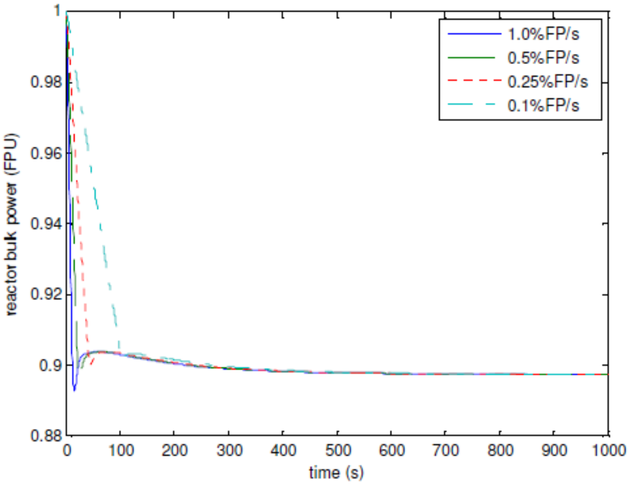


Figure 7 *Comparison of 4 power transients' simulations at different power changing rates*

Neutron flux dynamics within regional overpower protection detectors

The Regional Overpower Protection (ROP) system is designed to protect the reactor against overpowers in the fuel caused by either a local peaking or a general power increase in the reactor load level. Within the core, there are two ROP systems: one for each of the two shutdown systems - SDS1 and SDS2. Each ROP system consists of several fast-responding self-powered flux detectors. They are distributed throughout the core within SDS1 and SDS2 assemblies. Each ROP detector has been designed with a pre-set trip setpoint (TSP). The standard TSP for CANDU reactors is around 1.23 [3].

Figure 8 shows a typical ROP detector distribution for SDS1 within the center cross section of the core. **Figure 9** illustrates the dynamic process of the neutron flux variation within several selected detectors during the load-following operation. The trajectories in **Figure 9** demonstrate that none of the normalized neutron fluxes of the selected detectors are over the TSP, and thus the trip signal is not activated.

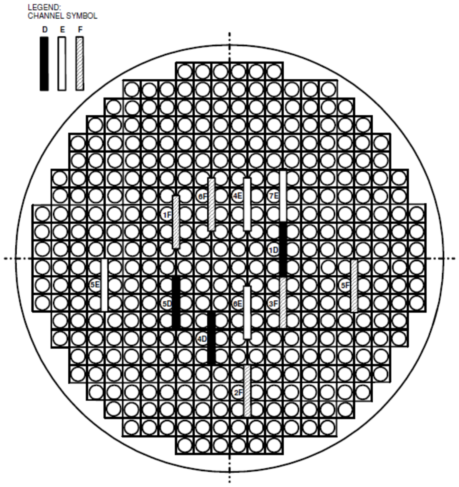


Figure 8 *ROP detector location for SDS1 within the center cross section of the core1.02*

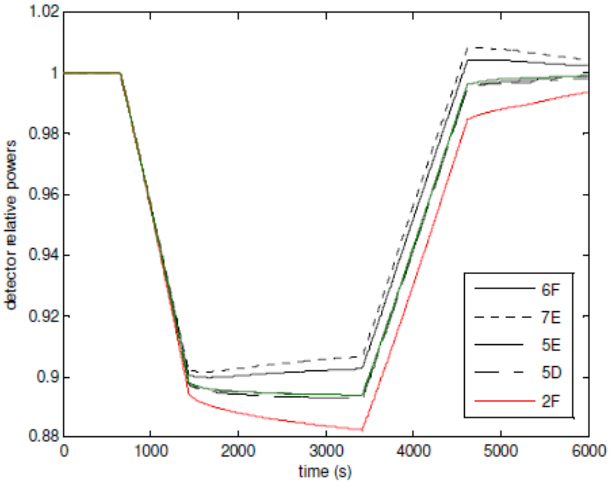


Figure 9 *Simulation results of the neutron flux varying within selected ROP detectors for load following process*

Core neutron flux distribution during transients

Under the RRS control, the shape of the reactor neutron flux distribution has to be close to its nominal design shape to ensure the reactor's operational safety and optimal performance. For illustrative purposes, the CANDU core is sliced into 12 layers of the same thickness, as shown in **Figure 10**, where the fourth layer from the right is chosen for subsequent illustrations. The central plane is also highlighted since it divides the reactor core into two symmetric halves. The neutron flux distributions modeled by the 3-D modal power is 1.0 FPU)

The variations of the neutron flux distribution on the fourth layer during the load synthesis model at the fourth layer are shown in **Figure 11** under 1.0 FPU reactor power. As can be seen in **Figure 11**, the modal synthesis method can provide much detail in terms of peaks and valleys in the core power distribution. In particular, it can be observed that due to the neutron absorption of the liquid zone controllers, there are seven notches distributed in the related zones, indicating reduced neutron flux.

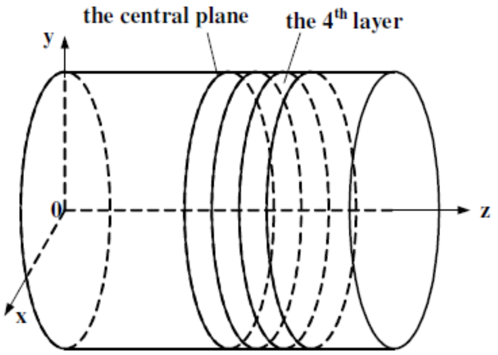


Figure 10 *The relative position of the fourth layer within the CANDU reactor core*

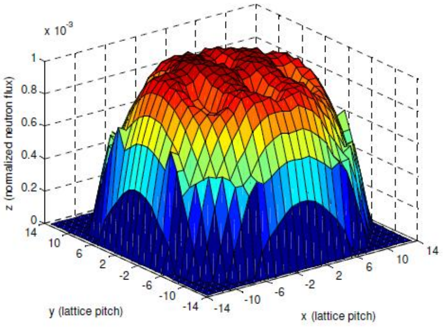
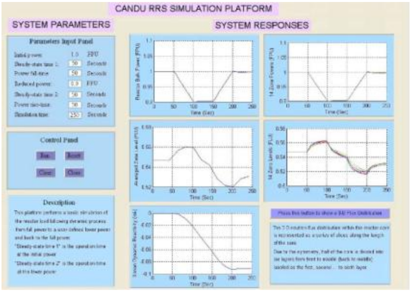


Figure 11 *Neutron flux distribution at the fourth layer along the z-direction (reactor power is 0.95 FPU)*

CANDU RRS Graphical User Interface (GUI)

A Graphical User Interface (GUI) allows users to perform tasks interactively. MATLAB GUI represents a convenient software environment for users to perform tasks such as creating and customizing plots, fitting curves and surfaces, and analyzing and filtering signals [4]. Users can also create custom GUIs for others to use - either by running them within MATLAB or as standalone applications that could be run independently in the MATLAB environment.
Figure 12 it can be seen that the basic system parameters can be inputted to the "Parameter Input Panel". After running, the reactor dynamic responses including reactor bulk power and zonal power responses, 14 zonal water levels and their averaged value, and Xenon build-up reactivity, could be depicted through the "System Responses" panel. Also, by pressing the blue strip button, the 3-D flux distribution within the core is represented, as shown in **Figure 13**. Furthermore, the user can modify the parameter values by "Parameters Input Panel" such that the corresponding system responses, in case of different transient conditions, can be generated.



Initial power 1.0 FPU
Steady-state time 1: 50 Seconds
Power fall-time 50 Seconds
Reduced power 0.9 FPU
Steady-state time 2: 50 Seconds
Power rise-time 50 Seconds
Simulation time 250 Seconds

Figure 12 *MATLAB GUI for CANDU RRS simulation platform*

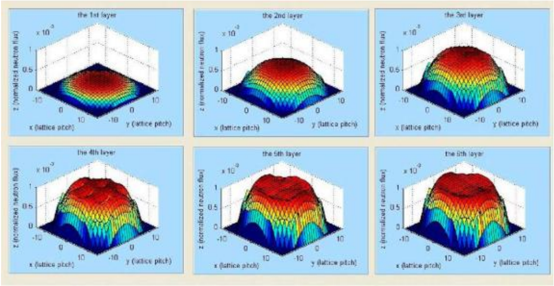


Figure 13 *3-D flux distribution module of the CANDU RRS GUI*

Conclusions

The evaluation of the performance of the 3-D modal synthesis based reactor kinetic model in a closed-loop environment is carried out in a MATLAB/SIMULINK based RRS simulation platform. A notable advantage of the 3-D model is the level of details that it can reveal as compared to the coupled point kinetic model. Using the developed RRS simulation platform, the reactor internal behaviours can be revealed during load-following tests. The test results are also benchmarked against measurements from an existing power plant. It can be concluded that the 3-D reactor model produces more realistic view of the core neutron flux distribution, which is closer to the real plant measurements than that from a coupled point kinetic model. It is also shown that, through a vectorization process, the computational load of the 3-D model is comparable with that of the 14-zone coupled point kinetic model. Furthermore, the developed GUI software package for RRS' implementation represents a user friendly and independent application environment for education training and industrial utilizations.

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