Complex System Simulator for the Time Dependent Simulation of Nuclear Power Systems

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Abstract

For the past several years, a full plant engineering simulation code has been under development in the Nuclear Engineering Department at North Carolina State University to simulate the dynamic response of Pressurized Water Reactor Systems. The software is used in the Department’s Reactor Systems course, as well as a number of other undergraduate courses to demonstrate the effectiveness of the plants control and protection systems and illustrate transient systems behavior during normal and off-normal operating conditions. The software has served as the basis of a Simulation Laboratory within the Department with the goal of providing a convenient, interactive platform for the design and analysis of reactor systems.

Introduction

Nuclear power plants are tightly coupled, complex systems. Changes in system parameters (e.g. flows, pressures, temperatures, etc.) at any location within the plant, can feed back affecting the behavior of the reactor core as well as other system components. This is further complicated by differences in plant design leading to completely different responses to the same initiating event. The Nuclear Engineering Department at North Carolina State University (NCSU), offers a senior level Reactor Systems course in which students gain an appreciation for interactions between the various plant components and control systems, eventually leading to the students being able to predict plant response to upset conditions. Historically, instruction involving plant response focused primarily on review of Chapter 15 type transients considered in Safety Analysis Reports, or was centered around class room discussion of “classic” accidents or off normal conditions with limited opportunity for students to engage in “what if ” scenarios. These activities are useful for demonstrating plant response, however Chapter 15 analyses generally are based on worst case assumptions involving limiting events where non-safety grade equipment and most control systems are assumed not to function. While appropriate for assessing safety, these type analyses often do not reflect normal plant response and provide no insight into the function or accident mitigating capabilities of non-safety grade auxiliary systems. Since it is likely that these systems would function under most accident conditions, students have little exposure to a broad range of accident scenarios or upset conditions they would likely experience as professional Nuclear Engineers. In addition, this approach does not allow for a quantitative assessment of the sensitivity of plant response to plant parameters, control strategies, control system setpoints and component size and capacity. To address these issues, systems simulation software has been developed that allows students to address these questions on their own, as well as giving the instructor an in class tool which could be used to broaden the discussion to hypothetical situations proposed by the students.

System Simulator

The accurate prediction of plant behavior during normal and off normal conditions requires accurate thermal-hydraulic models, as well as provisions for the simulation of auxiliary systems, mechanical components and control functions. While these capabilities exist to some degree in large reactor safety codes such as TRAC[1] and RELAP5[2], these codes were developed primarily for the simulation of loss of coolant and other design basis accidents where most normal control functions are assumed to be inactive. In addition, codes of this type generally require a long learning curve and the source code is difficult, if not impossible, to modify. Here, the emphasis is on simulation of plant response over the full range of "normal" or "near normal" operating conditions. Particularly important is the impact of control systems on plant response and stability.

Over the past several years, a full plant engineering simulation code has been under development to simulate the dynamic response of Light Water Reactor Systems during normal operational transients as well as a limited number of design basis events (non LOCA). The model currently is capable of simulating multi-loop PWR systems with U-Tube steam generators, allowing for asymmetric loop operation. Both primary and secondary sides are represented, including balance of plant and control systems. Plant protection systems are modeled including the normal spectrum of reactor trips and engineered safety features. The reactor coolant system model contains component models for the reactor core, pressurizer, reactor coolant pumps and aspects of the chemical volume control system (CVCS). Reactor power is obtained by a point kinetics model, with reactivity feedback via control rods, doppler, moderator temperature and soluable boron. A boron transport model is included to allow for simulation of transients associated with misoperation of the CVCS. A hot channel model is also included to allow for calculation of critical heat flux.

The steam generator model is based on a four equation drift flux model which allows for nonequilibrium treatment of the liquid phase. Level tracking logic is included to allow for simulation of vertical stratified flows and accurate predictions of steam generator liquid levels. The steam generator model also allows for cross flow between the hot and cold sides of the U-tubes and includes provisions for integral economizers including control logic to split feed flow between the economizer and steam generator downcomer. The feed train is modeled as up to three parallel feed pumps connected at a common manifold feeding the steam generators. Currently the feed pumps are modeled as fixed speed, such that feed control is accomplished by modulation of the feed control valves. Modifications to allow for variable speed pumps are relatively straight forward and could be incorporated with minimum effort. The model has been benchmarked against a number of transients included in the McGuire Final Safety Analysis Report (FSAR)[3] .

User Interface

For a simulator of this type to be effective, it must execute quickly, require minimal input from the students and present the output in a concise and meaningful manner. The computational models used in the current version of the simulator have been designed for speed and efficiency. Tests over a range of transients show the model to be much faster than real time on current generation workstations and PC's. Input and output are by menus designed to be intuitive and require minimal up front work by the user. Systems simulations of this type typically require large amounts of plant specific geometric and component information. Input files have been generated for "typical" reactor designs, which are menu selectable by the user. Examples include Four-Loop Westinghouse and CE System 80+ designs. Once a design has been selected, options are available for changing parameters such as reactivity coefficients, trip and safety system setpoints, control system setpoints, pressurizer heater capacity, number and capacity of main steam safety valves, etc. to facilitate sensitivity studies as well as letting the user custom design a plant if desired. In addition, the user has the option to enable/disable a number of control functions including reactor trips. For example, the user can place control rods in manual or automatic mode, with manual mode implying no control rod motion during a transient. If automatic mode is selected, the control rods move according to a user supplied program. Additional options include reactor trip on turbine trip, deactivation of the turbine bypass system, loss of off site power coincident with turbine trip as well as others.

A broad spectrum of design basis accidents, operational transients and initial conditions are also available through interactive menus. Initial power level and plant state (beginning of cycle or end of cycle) are menu selectable. Upset conditions include (but are not limited to) normal operational transients such as step and ramp load changes, and the suite of transients normally assumed in Chapter 15 safety analyses. For example, under- and over-cooling accidents such as loss of a feed pump, or inadvertent opening of a steam safety valve can be selected. Unlike the Chapter 15 analyses however, the student is able to analyze these transients with all or none of the normal auxiliary and control systems active. This flexibility in the software has had the added benefit of providing students a relatively simple to use, systems design tool in addition to providing a platform for the analysis of system transients.

The output package currently provides for line graph displays of simulation results. Graphs are again menu selectable and ordered around subsystems and components, with the number and type of graphs a user option. Control and safety system setpoints can be displayed at the discretion of the user. Additional output features include a trip and control systems log and a Simulation Summary. The trip and control systems log provides the time and sequence of trip and safety system actuation signals. The Simulation Summary provides an output of all simulation parameters and user selected options.

Future Developments

The current version of the reactor simulation program has undergone extensive testing and evaluation in the Reactor Systems class, and has also be used in other undergraduate courses to illustrate systems related phenomena. Feedback from instructors and students using the software are driving the development of additional capabilities as well as improvements in the user interfaces. One extension of the simulation software has been the development of component design modules based on the component models used in the simulator. These design modules use the same physical and computational models utilized in the simulator and allow the student to perform design studies of individual components in the absence of feedback from control systems and interactions with other plant systems. Once a component design has been completed, the design module creates an input file which can be accessed by the simulator such that the impact of the design change on the system response can be evaluated. A module for the design of U-Tube steam generators has been completed. Additional modules are under development for the pressurizer and reactor core.

The simulation software has provided the basis for development of a Simulation Laboratory within the Nuclear Engineering Department. The Simulation Laboratory currently consists of six dedicated SUN workstations which can be configured to run in a batch/post processing mode, allowing students to individually access the simulation software, or in a dedicated mode in which real time interaction with the software is possible. In the dedicated mode, the simulator operates as a normal training simulator where output is provided as both plant mimics and real time traces of plant parameters. Long term development plans for the simulation laboratory include the development of a “virtual” control room, which in addition to the educational opportunities would provide a research platform for the development of advanced control systems, man-machine interfaces and advanced control room designs.

Bibliography

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