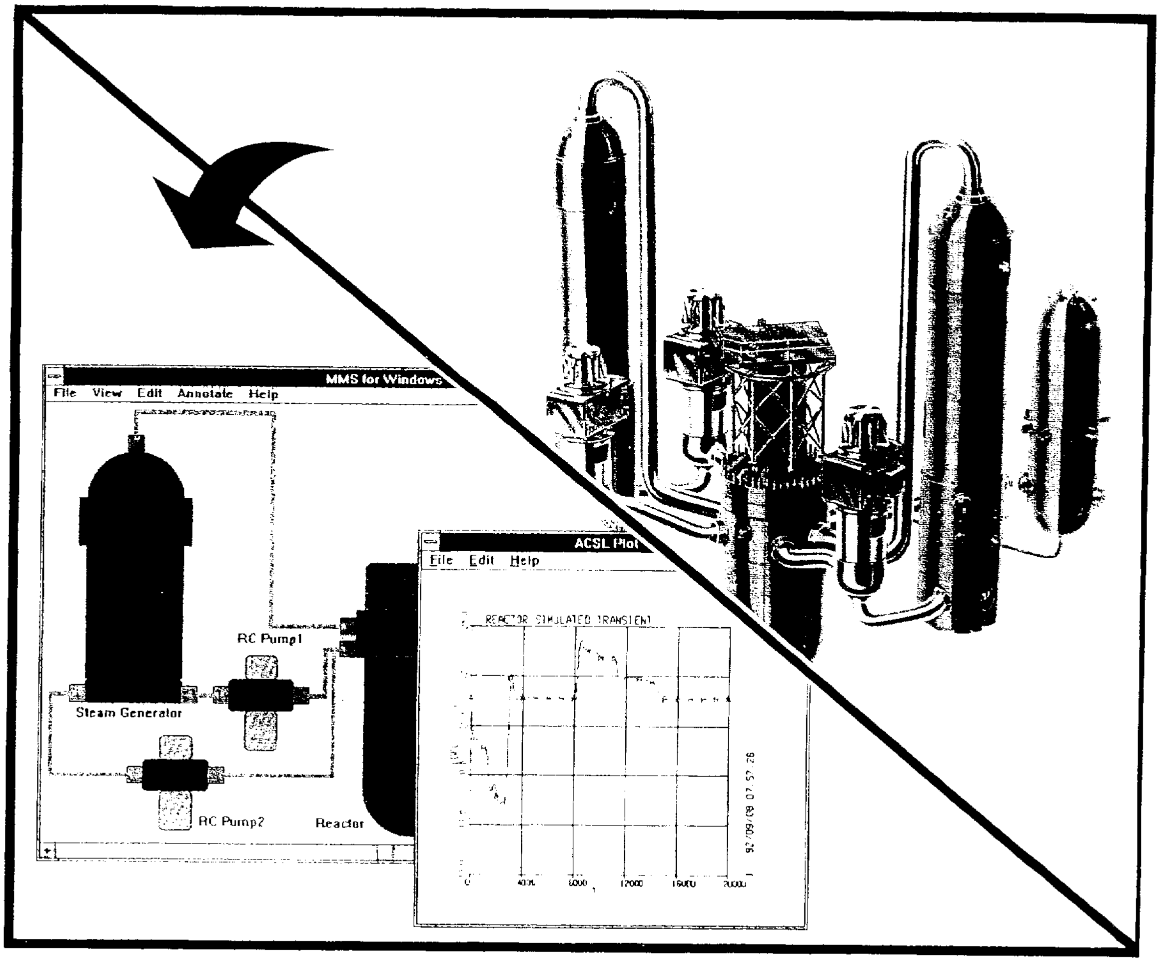

NUCLEAR PLANT PERFORMANCE ANALYSIS USING THE MODULAR MODELING SYSTEM

By

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Abstract

The Tennessee Valley Authority has resumed construction and licensing of its Bellefonte Nuclear Plant. As part of the engineering effort for plant completion, B&W Nuclear Technologies was contracted to develop the Bellefonte Plant Model, a full-scope engineering model of the plant and its control systems. The Modular Modeling System was used because it produces models that can be changed easily to support the evaluation of alternatives in plant design and operation. In addition, as new technology is developed for the Modular Modeling System, it becomes available for use in the Bellefonte Plant Model.

Background

The Bellefonte Nuclear Plant has a B&W 205 Nuclear Steam Supply System (NSSS) rated at 3620 MW. Construction was started in 1974 and deferred in 1988 because projected demand did not require the plant to be online until the early 2000s. Unit 1 is approximately 75% complete and Unit 2 approximately 50%. In March of 1993, the Tennessee Valley Authority issued the letter to the NRC to reactivate construction.

As part of the engineering effort for plant completion, B&W Nuclear Technologies was contracted to develop the Bellefonte Plant Model (BPM), a dynamic simulation of the

Bellefonte plant. The Bellefonte secondary plant system has several unique design features and the potential for upgrades based on the experience gained from the operation of the Mülheim-Kärlich plant, which also has a B&W 205 NSSS. The BPM is a full-scope engineering model of the plant and its control systems developed as a tool to evaluate engineering enhancements and concerns.

As a comprehensive plant model, the BPM will permit the effective examination of the following types of issues:

- The Bellefonte secondary plant system is very closely coupled. Because there is a high degree of coupling between the feedwater, condensate, and steam portions of the plant, a component upset will cascade quickly down the system and could significantly affect the entire secondary system. For example, the effects of the loss of a hotwell or condensate booster pump can immediately propagate to the main feedwater pumps and affect flows to the steam generators because of the absence of a deaerating feedwater heater.

- The Bellefonte secondary plant system has several features designed to increase thermal efficiencies. Some of these features use component configurations that merit examination for unusual system sensitivity and other problems. Examples of such component configurations are feedwater pump turbine condensers which are cooled with condensate flow, a moisture separator reheater drain blowdown heat exchanger that recovers energy in the drains, pegging steam to provide appreciable low power and post-trip feedwater heating, and the overload valve to increase the turbine generator capacity.

- The Mülheim-Kärlich plant was the first B&W-designed 205 fuel assembly (FA) plant, using Integral Economizer Once-Through Steam Generators (IEOTSGs), to become operational. Because IEOTSGs differ from the 177 FA plants that used Once-Through Steam Generators, unique operational lessons were learned from operation at Mülheim-Kärlich. These lessons could potentially lead to modification of the turbine control system logic, the feedwater level control at low power, etc.

- There is a need to evaluate and resolve Safety Performance Improvement Program recommendations relating to the performance of the steam, feedwater, and condensate systems.

The Modular Modeling System

The Modular Modeling System (MMS) is a software system used to build dynamic simulations of fossil and nuclear power plants. The MMS was used for developing the BPM because it simplifies the development of dynamic simulations by providing pre-engineered software modules to simulate plant systems and subsystems. The central feature of the MMS methodology, illustrated in Figure 1, is that models of individual components are prepared in the form of software modules that can be selected and interconnected as components are interconnected in the plant.

The BPM uses a newly developed library of modules that model low flow, reverse flow, and natural circulation. Without compromising modularity, these new modules solve algebraic pressure-flow relations simultaneously without requiring introduction of connect nodes that were required by older formulations of MMS. Eliminating connect nodes eliminates their artificial compressibility terms and the accompanying inaccuracies and numerical difficulties.

At present, the new library includes modules for the feedwater/condensate flow paths. New modules that eliminate the need for connect nodes in the steam flow paths are currently under development. The BPM will be able to utilize new modules and new MMS technology as it becomes available.

An MMS module for the Integral Economizer Once-Through Steam Generator was developed for the BPM. The module was designed for speed of execution over a wide range of power. The secondary side of the the generator is modeled with regions with moving boundaries -- one region each for the subcooled, saturated, and superheat conditions. The subcooled region is further subdivided into multiple nodes, with mass and energy equations solved for each node. Pressure loss is modeled using a quasi-static momentum equation. The heat transfer relations are simplified in that tube metal heat capacity, transition boiling or CHF limitation, and subcooled boiling are not modeled. A drift flux void fraction model is used. Boundary conditions on the primary side are inlet flow, inlet temperature, and a pressure assumed to be constant with respect to space on the steam generator primary side. On the secondary side, boundary conditions are inlet flow, inlet temperature, and outlet steam flow rate.

ACSL

The MMS is written using the ACSL (Advanced Continuous Simulation Language) simulation language. ACSL facilitates the development of simulations by providing:
- Macro capability
- Automatic sorting of modeling equations
- Translation to Fortran

The user develops an MMS model by selecting the modules he needs, and specifying their input parameters and how they are to be interconnected. The ACSL translator produces a Fortran program, which is compiled and linked with an ACSL and an MMS runtime library to produce an executable file. The user can control the execution of the simulation by using ACSL runtime commands to:
- Plot or print any variable
- Change the value of any parameter to simulate operator actions or malfunctions
- Query the value of any variable in the simulation

- Pause and continue a transient
- Save the state of the simulation
- Restore the state of the simulation from any previously saved state
- Choose integration algorithm

Level 10 of ACSL provides several new features, including 31-character variable names and additional linear analysis capabilities. The most significant new feature of level 10, however, is support for double precision calculations. Performing calculations in double precision greatly reduces numerical noise caused by round-off errors, thereby improving the convergence characteristics of numerical methods used to solve the modeling equations.

Scope of the BPM

The BPM includes all components and required control systems necessary to evaluate the plant design, including normal plant operation and transients due to operational failure that lead to turbine trips or other major plant upset. Figures 2 and 3 show schematics of the thermal-hydraulic components modeled for the primary and secondary system respectively. Figures 4 and 5 are simplified schematics of the ICS, pressurizer controls, and the steamline dump control. Tables 1 and 2 summarize the components and systems modeled. The components and control systems modeled by the BPM are listed in more detail in Appendix A.

Applications of the BPM

The BPM is to be used to simulate operational transients and anticipated operational occurrences. The following is a partial list of transients that the BPM is to simulate:

- Reactor trip with rapid feedwater reduction
- Turbine trip
- ICS signal and control element failures
- Stops/starts of individual BOP pumps (i.e., feedwater, condensate, etc.)
- Loss of main feedwater pump at 100% power
- Turbomat controller evaluation
- Steam generator level control at low power
- Low power operation
- Demineralizer bypass valve operation
- Inadvertent opening of recirculation valves
- Plant runback on low NPSH to the main feedwater pump
- Main feedwater pump turbine control system with ICS
- Instabilities in heater drain pump recirculation valves
- Evaluation of alarm setpoints vs. trip setpoints
- Partial load rejection with turbine fast valving

Status and plans

The BPM uses a combination of standard MMS modules, newly developed modules, and ACSL coding. Because the BPM is a new and complex simulation, changes in performance are expected as the model evolves. At present, the BPM contains 400 state variables and takes thirty milliseconds of computer time to perform a single evaluation of all derivatives. Although real-time performance was not a requirement for the BPM, it seems to be achievable. The limiting time constants are associated with the connect nodes in the turbine modules. These connect nodes will be eliminated when the turbine modules are upgraded to employ the same methods used to eliminate connect nodes in the feedwater system.

At present, the integration option used by the BPM is the forward Euler algorithm instead of the Gear algorithm normally used by MMS. The Gear algorithm, a variable step size algorithm, is usually more efficient because it automatically increases its time step size using error criteria specified by the user. However, the modeling of on/off controllers (the rod controller, for example) in the BPM eliminates this advantage.

On/off controllers cause the Gear algorithm to relinearize and to change time step size, for even steady state conditions. The time required by the Gear algorithm to linearize the modeling equations and to change the time-step size increases with the square of the number of state variables. The net result for a simulation as large as the BPM is that the Euler algorithm runs more quickly than the Gear algorithm.

The effect of step size on the behavior of models with on-off controllers is more straightforward for a fixed step algorithm like Euler than for a variable step size algorithm like Gear. This advantage is important during the evaluation of a model of a large plant, which is still in the design stage and contains many untuned control systems. After the control systems are tuned and if the Gear is then the more efficient algorithm, the BPM can use it by simply changing the value of a single variable.

As the current plant design is re-evaluated, plant parameters are being recalculated The new and updated data accumulated since the beginning of the BPM development are in the process of being incorporated into the BPM. As the design of the Bellefonte Plant evolves, the configuration of the BPM will be modified to evaluate the performance of alternative plant configurations.

Appendix B shows the specifications of a graphical user interface for the BPM using the Windows NT operating system.

In conclusion, the modularity and flexibility of the MMS enable the BPM to use newly upgraded modules, to choose integration techniques, and to accommodate changes in plant configuration and data.

Acknowledgments

The development of BPM was performed and supported by many engineers and analysts. The authors would like to acknowledge their contributions by identifying them here. B&W Nuclear Technologies: R. B. Brownell, E. F. Carr, D. M. Craddock, V. J. Galan, C. A. Jones, R. W. Moore, P. W. Ploch, D. J. Skulina, A. J. Streath, and K. W. Turner. Stone & Webster Engineering Corporation: Y. Cho, D. E. Labbe, and J. A. Rovnak for their contribution to the modeling of the control logic for the condensate/feedwater systems.

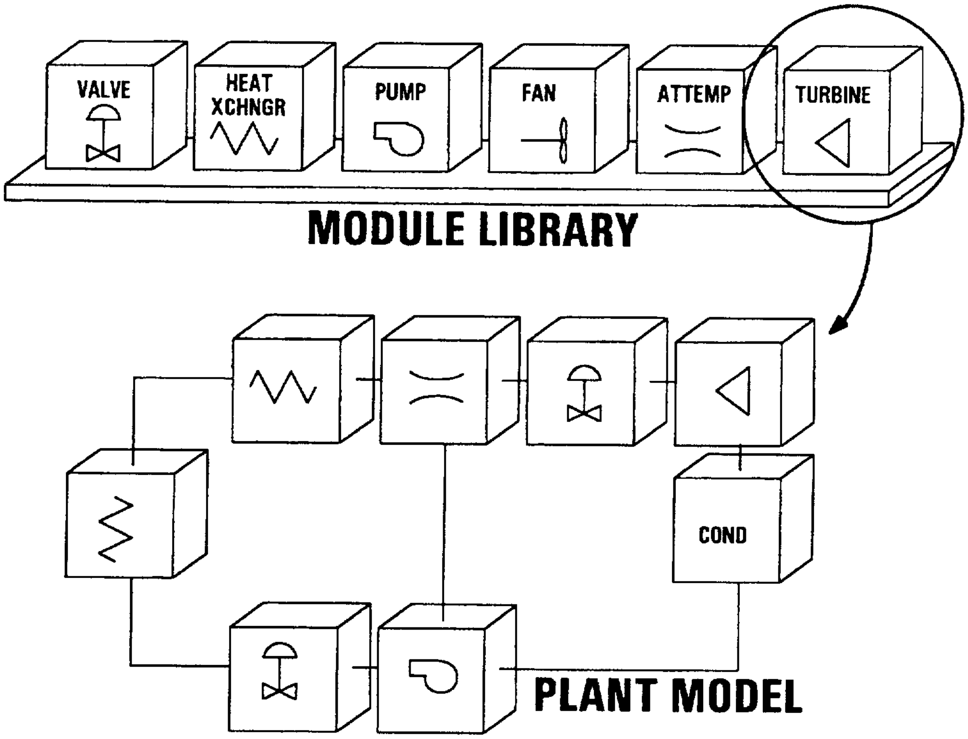


Figure 1.
The Modular Modeling System Concept

Table 1

Components and Systems Included in the BPM:

- Reactor
- Pressurizer
- Integral economizer once-through steam generators
- Reactor coolant pumps
- Steamlines
- High and low pressure steam turbines
- Moisture separator reheaters
- Turbine bypass system
- Extraction steam system
- Condensate system (2 trains)
- Feedwater system (2 trains)
- HP heater drain system
- LP heater drain system
- Electrical generator

Table 2

Plant Controls and Protection Systems Included in the BPM

- Integrated Control System -- B&W's system for coordinated control of the reactor, steam generator, steam turbine, and steam dump to meet demand for electrical output.
- Pressurizer pressure and level controls
- Control rod drive control system
- Turbotrol turbine control system -- Brown Boveri Company's system for control and protection of the turbine
- Other local control systems for BOP -- Level control for all tanks and feedwater heaters, feedwater heater isolation and bypass logic, pump on/off logic.
- Reactor protection system

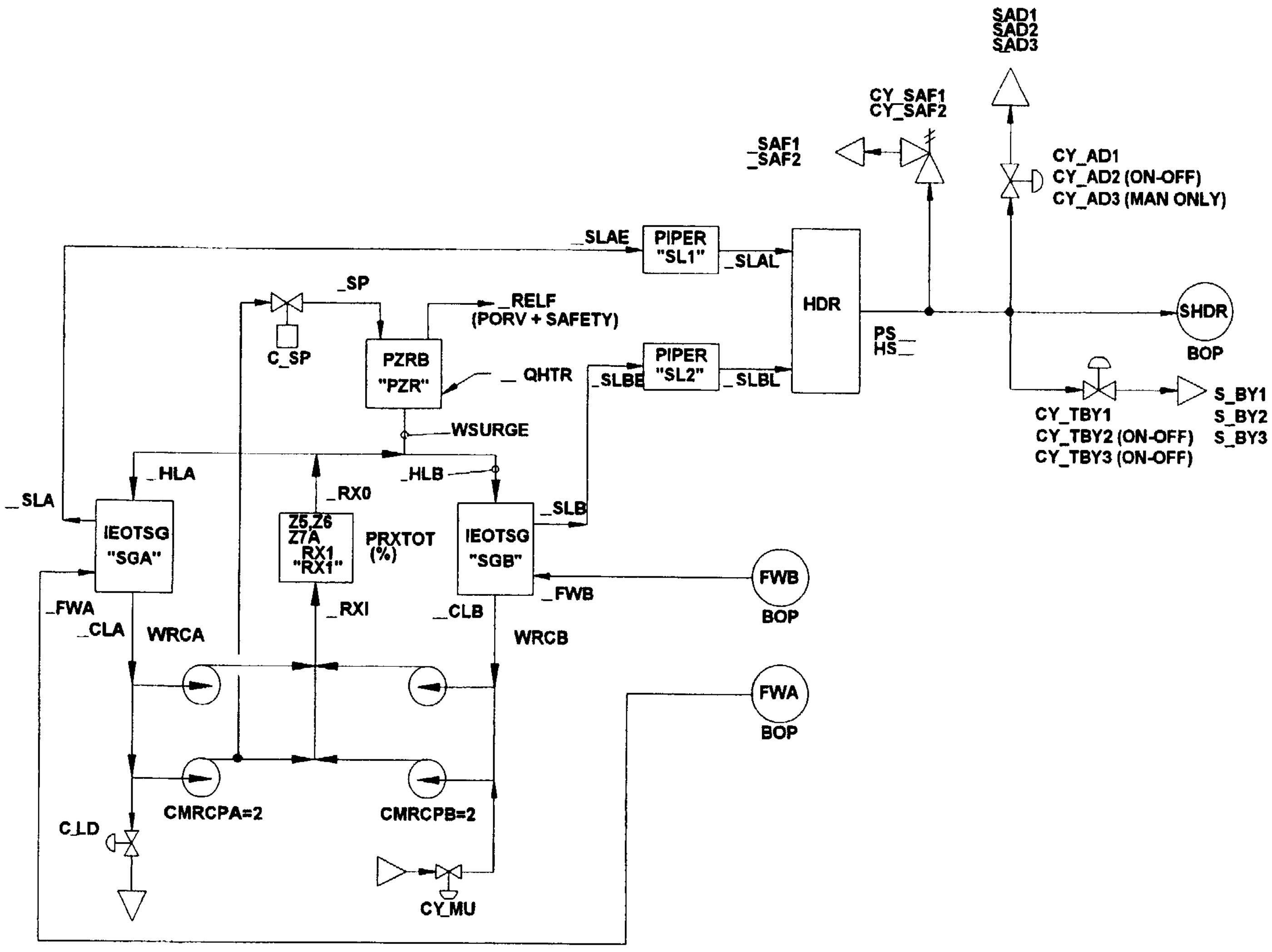


Figure 2.
Reactor Coolant System and Steamline Schematic

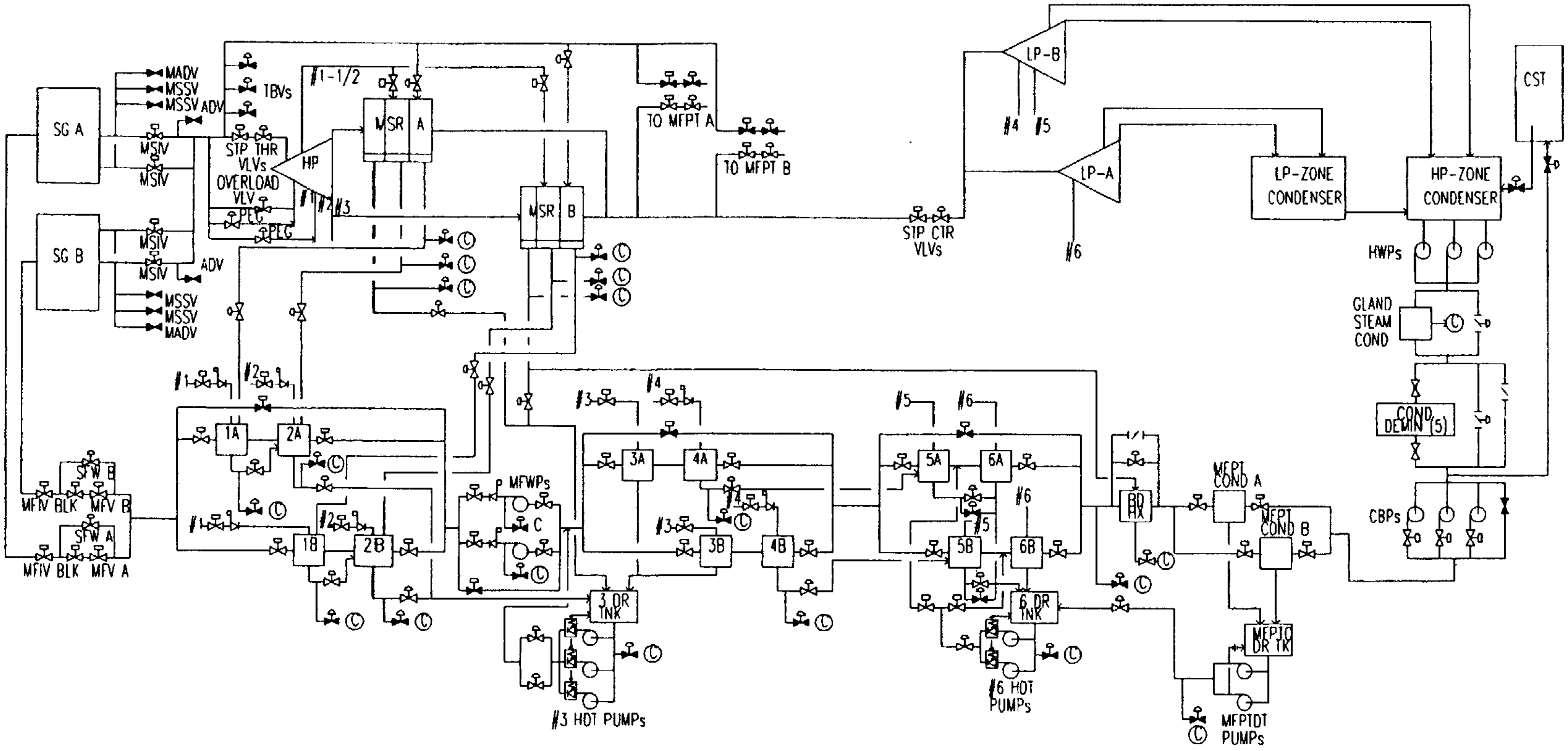


Figure 3.
Balance of Plant Schematic for the Bellefonte Plant Model

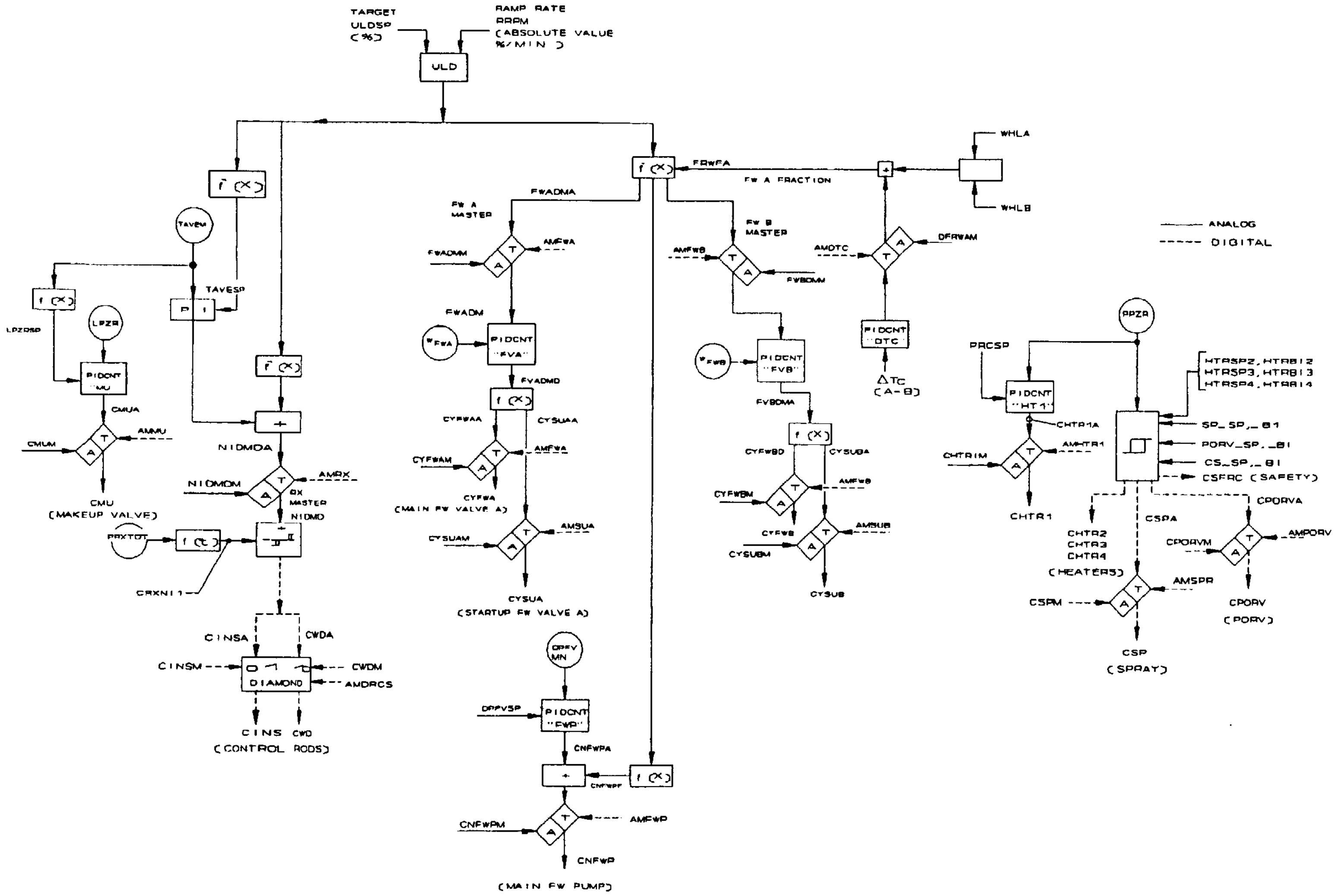


Figure 4.
Simplified Control System Model (Reactor, Feedwater, Pressurizer)

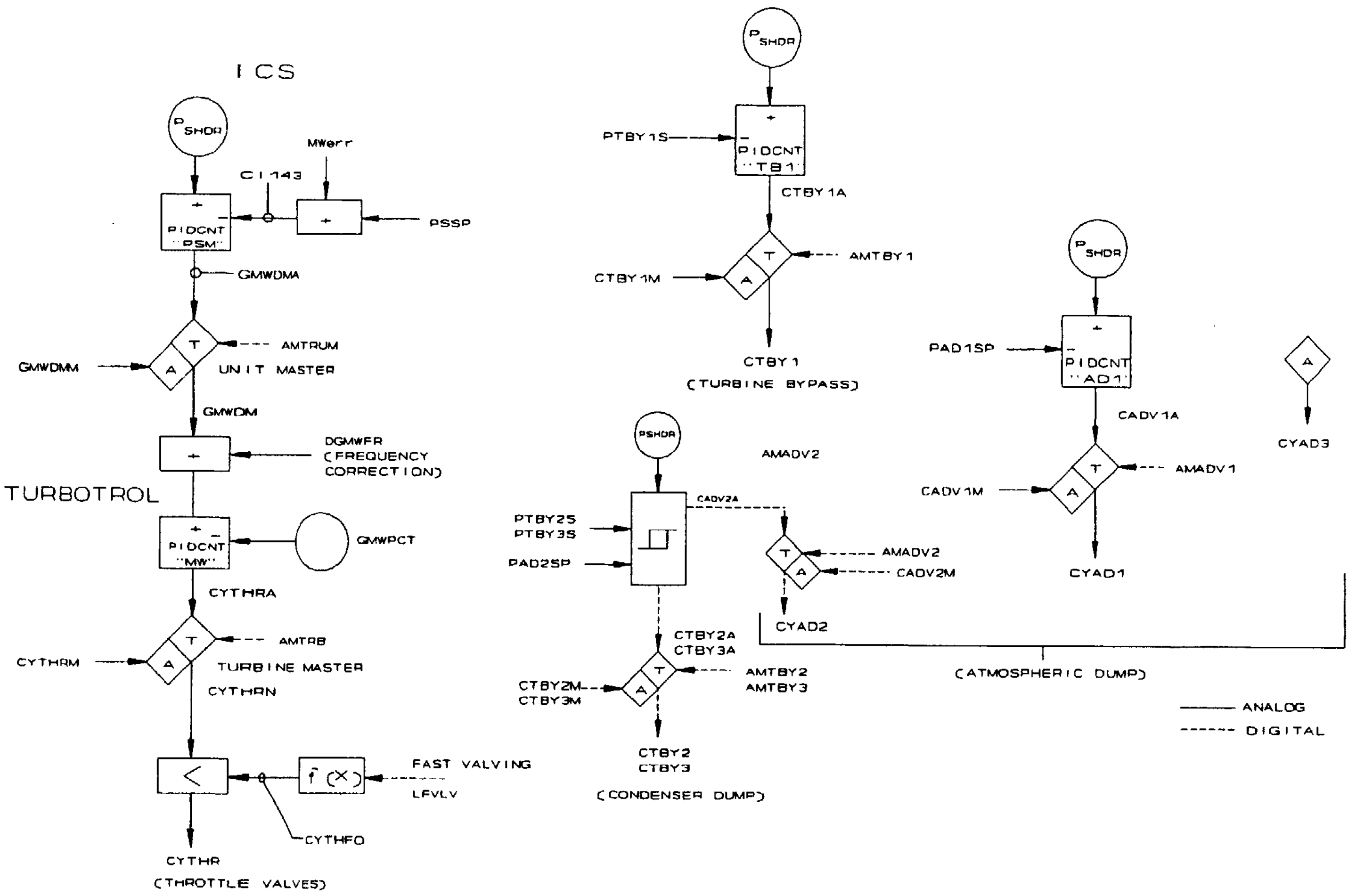


Figure 5.
Simplified Control System Model (Turbine and Steam Dump)

Appendix A
Components and Systems Modeled for The Bellefonte Plant Model

Primary loop:
Hot legs(2), cold legs(2), loop flow tables, makeup flow with one/two pump operation with control based on pressurizer level control, and letdown flow

Reactor core:
Average power fuel pin model, neutron kinetics, delayed neutrons, decay heat , 5 rod groups, and boron concentration

Pressurizer:
Non-equilibrium, level controls, spray, relief valve, heaters, surge line, interfacial/metal wall condensation, bubble rise, and rainout

Steam generator:
Heat transfer correlations covering subcooled to superheat conditions, mass and energy dynamics, and drift flux for void fraction on secondary side

Condensate System:
- Condensate storage tank
- Condenser (zone A and zone B) with pressure and level sensors
- Hotwell pumps/motors
- Demineralizer and bypass valve
- Valve bypass control to condensate storage tank
- Condensate booster pumps/motor and controls
- MFW pump turbine condensers, tank, and isolation valves
- MS/RH blowdown heat exchanger and bypass valve and controls
- "Short cycle" recirculation line valve
- FW heaters 5A & 5B and 6A & 6B, isolation valves and bypass valve
- FW heaters 3A & 3B and 4A & 4B, isolation valves and bypass valve
- No. 6 heater drain system: tank, pumps, and valves
- No. 3 heater drain system: tank, pumps, and valves

Feedwater (FW) System:

- Main feedwater pump turbine (MFPT) and controls including low and high pressure steam control valves
- Main feedwater pumps (MFWP) A & B
- MFWP recirculation valves and controls and line to condenser
- MFWP isolation and bypass valves
- FW Heaters 1A & 1B and 2A & 2B, isolation valves and bypass valve
- "Long cycle" recirculation valves
- Startup control valves
- Main FW control valves, block valves, and isolation valves

Main steam system:

- Steamline and steamline valves:
  - Turbine bypass system valves (condenser modulating and on/off dump and atmospheric dump), main turbine governor valve, intercept valves, turbine stop valve, relief, and isolation valves
  - HP/LP turbine with reverse flow capability through 1st extraction line

Electrical generator

ICS and Turbomat:

- ICS additions:
  - Fast valving (ICS & Turbomat)
  - Rapid FW reduction

Description of other local controls for balance of plant:

- Main turbine moisture separator/reheater (MS/RH) drain system:
  - MS/RH A and B: each MS/RH consists of two moisture separators, two first-stage reheaters, and two second-stage reheaters. Moisture separators drain into the No. 3 drain tank, 30% to 100% of the full-load drains of one MS/RH may be directed through a regenerative moisture separator blowdown heat exchanger to the condenser. The MS/RH drain system has a total of four first stage and four second stage reheater drain tanks. Each reheater drain tank has: (a) level sensor and control valve draining to the corresponding FW heater and to the condenser, (b) hi-hi level sensor and reheat isolation steam valves to reheater and opposite reheater bundle serving the same LP turbine, and (c) signal to Turbomat. The moisture separator drain pot has: (a) level sensor and control valves to No. 3 drain tank and to condenser and (b) hi-hi level sensor switch to trip turbine.
- No. 1 FW Heaters:
  - (a) level sensor and modulating control valves draining to FW heater No. 2, (b) high-level sensor that opens valve draining to condenser, (c) emergency high-level sensor (operates on FW heaters No. 1 & 2 of same string) that closes extraction steam isolation valves, closes FW No. 1 & 2 isolation valves and opens bypass valve (unit load > 65%), and closes reheater 1 & 2 drains and vents into No.1 and

2 FW heaters and (d) throttling and check valves to isolate heaters from main steam pegging steam and positive closing reverse flow valves.

No. 2 FW heaters:

(a) level sensor and modulating control valves draining to FW heater No. 2, (b) high-level sensor that opens valve draining to condenser, (c) emergency high-level sensor sharing same OR gate with No. 1 FW heater and (d) throttling and check valves to isolate heaters from the main steam pegging steam and positive closing reverse flow valves.

No. 3 FW heaters:

Emergency high-level sensor trips the turbine, closes extraction steam isolation valves to No. 3 and No. 4 heaters, closes FW isolation valves for No. 3 and No. 4 heaters, opens heaters FW bypass valve and closes extraction steam valve to No. 4 heater.

No. 3 heater drain tank:

(a) level sensor and a pump differential pressure sensor and two modulating control valves at the discharge of the heater drain pumps, (b) emergency high-level sensor that opens valve draining to condenser and controls moisture separator and No. 2 FW heater drain valves, (c) emergency high-high level sensor to pull condenser vacuum breaker, (d) low-level sensor to trip drain pumps and open valve to warming line to main condenser, and (e) initial condenser bypass, 2 of 3 drain tank pumps started at unit load > 40%, third pump auto starts at 65% unit load, condenser bypass valve (for loss of a pump).

No. 3 heater drain tank recirculation control valves:

These valves have an internal mechanism for control of recirculation control and may have to be simulated using a conventional valve and external control loop arrangement.

No. 4 FW heaters:

(a) level sensor and modulating control valves draining to No. 5 FW heater and (b) emergency high-level sensor shares same OR gate with No. 3 FW heater.

No. 5 FW heaters:

(a) level sensor and modulating control valves draining to the No. 6 FW heater drain tank, and (b) emergency high level sensor, No. 4 FW heater drain valve, condenser dump valve, No. 5 & 6 FW heater isolation valves and bypass vale, No. 6 drain pumped forward isolation valve (string A or B) and an emergency hi-hi sensor to pull condenser vacuum breaker.

No. 6 FW heater:

Emergency hi-hi and high-level sensor feed into the same OR gate as the No. 5 FW heater.

No. 6 FW heater drain tank:

(a) level sensor requirements and implementation same as No. 3 FW heater drain tank, (b) initial condenser bypass, two drain tank pumps started at unit load > 40% and (c) a low-level sensor trips drain pumps and opens valve to main condenser.

No. 6 heater drain tank recirculation control valves:

Refer to above item for No. 3 heater drain tank recirculation valves.

FW pump turbine condensers:
  High vacuum MFPT trip.

MFPT condenser drain tank:
  (a) two drain pumps (first pump starts, second pump started by low differential pressure signal across the pumps), (b) low-level sensor trips pumps, (c) level sensor and modulating control valve at drain pump discharge and (d) high-level sensor and condenser drain valve.

Extraction steam system:
  Motor-operated isolation valves for extraction steam lines to Nos. 1, 2, 3, and 4 FW heaters and to MS/RH and positive closing reverse flow valves to FW heaters Nos. 1, 2, 3 and 4.

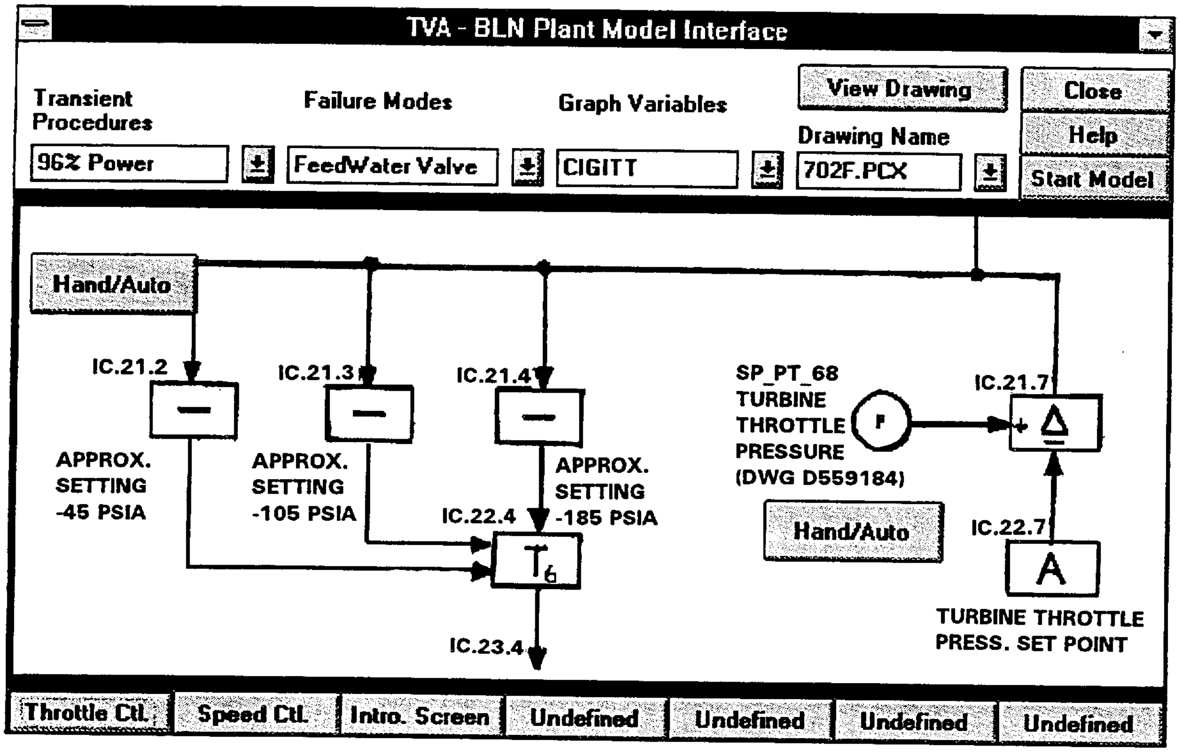
Overload valve:
  3-way valve that allows 108% of rated load, and controls (turbine control system).

Pegging steam to Nos. 1 and 2 FW heaters

Appendix B
Specification for a Graphical User Interface for the Bellefonte Plant Model

Introduction

The Bellefonte Plant Model (BPM) is a MMS model used for engineering analysis of the dynamic performance of the Bellefonte plant. Potential users of the system have expressed the desire to operate the model with a graphical user interface.



TVA - BLN Plant Model Interface

Transient Procedures: 96% Power

Failure Modes: FeedWater Valve

Graph Variables: CIGITT

Drawing Name: 702F.PCX

Figure B-1. Interface Window

Multitasking features of the Microsoft Windows operating system allow both the BPM and the *interface* to operate concurrently on the same PC. ACSL has provided features that allow an *interface* to be connected with the model without making changes to the source code of the model. The combination of these two factors permits a flexible *interface* that can allow the model to be run using ACSL only, or to be controlled by the *interface*.

Interface Configuration

Figure B-1 shows the configuration of the *interface*. The *interface* window is a non-sizable window broken into three horizontal panes. Minimization of the window is allowed.

Top Pane

The top pane consists of a series of MS-Windows Combination Controls that provide a list of choices in a drop down menu when the down arrow is selected. Three major functional features of the *interface* are controlled by these controls -- pre-configured "Transient Procedures," pre-configured "Failure Modes," and selection of "Graph Variables" for runtime graphing. Runtime graphing is accomplished through a standalone program that can be started from the *interface*.

System drawings used to document the BPM control system can be viewed using the fourth combination box, "Drawing Name." In the initial version, all drawing files are stored in PCX file format and can be viewed in Paintbrush by clicking the "View Drawing" button with a file selected. In later versions, viewer software can be provided to display the files in any standard format selected for documentation.

Buttons are provided in the upper right of the top pane for closing the *interface*, obtaining on-line help, and starting the model.

Center Pane

Schematics, drawings, and other graphics are displayed in the center pane. Buttons or other interactive controls can be placed on the display as needed for each view. The number of views available and the number of controls on the display are not limited and can be pre-configured as needed.

Bottom Pane

The bottom pane is a array of buttons used to select the view in the center pane at any time. Contents of the controls in the upper pane can also be adjusted to each view as necessary.

Capabilities

This program is an *interface* shell for the BPM model running in the ACSL environment. As such, there is an overlap of capabilities and functions that are more efficiently done directly in the ACSL environment. Following is a list of functional capabilities and how they are implemented.

1) Setting Control System Gains - The *interface* will provide pre-configured controls on the display pane for accessing the gains, setpoints, and other attributes of controllers. Any controllers that do not have display pane controls can easily be set using the ACSL command line features or the ACSL menus.

2) Select Transients, Time of Initiation, and Power Levels - This is a function of the ACSL procedures and LOAD command. The upper pane Transients control executes predefined ACSL procedures. Procedures can be modified and/or added to the transient list as needed. Personnel familiar with the ACSL procedural can create new transients as needed and add them to the *interface*.

3) Access to Plant Variables - All variables can be set with the ACSL command line and menus. Any *interface* display controls will set or get the values of program variables as needed. The controls on the display pane set the value of the variables during model execution, which provides the user interactive control capability during runtime. The ACSL set command requires stopping and restarting the model.

4) Selecting Control Signal and Device Failures - All predefined failures can be accessed through the *interface*. In addition, other types of failures may be simulated through the setting of certain setpoints or other variables using ACSL. All pre-configured control signal failures will support 0%, midrange and 100% values.

5) Interrupting, Configuring, and Restarting or Continuing the Model - The model can be started, stopped, and restarted or continued at any time using the *interface* or ACSL. Any configuration commands that the *interface* supports will be available with the model running or stopped.

6) Runtime Graphics - A runtime graphing program will be provided. This will allow for inspection of variables while the model is running. Data will be able to be saved into a file for import into a graphing program.

7) Graphing of Simulation Results - ACSL provides the ability to combine the results of multiple transient simulations, change scales and have multiple Y-axes. The data from the output statement are available in the log file and can be imported into graphing programs.

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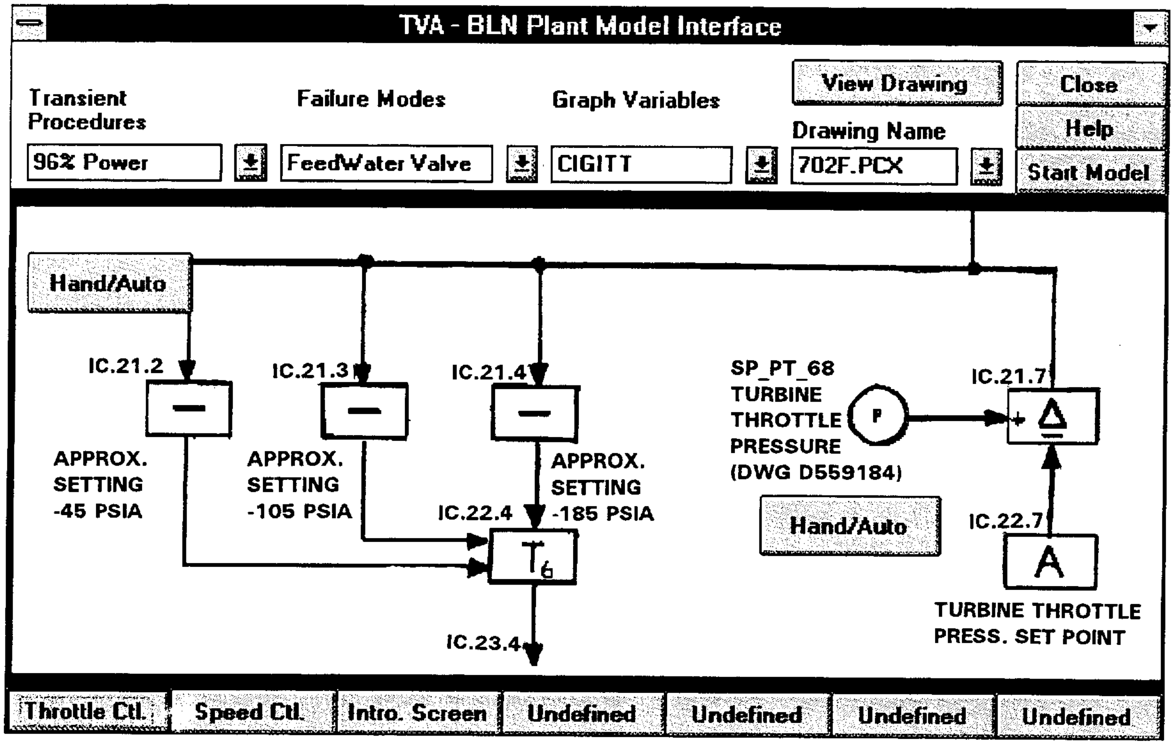

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