MMS APPLICATIONS FOR TRAINING AND FOR CONTROL SYSTEMS & PROCESS DEVELOPMENT

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INTRODUCTION

The availability of affordable and high-speed **personal computers (PCs)**, **central processor units (cpu)** (e.g., DEC Alpha, Intel's Pentium), and video graphics; advanced and user-friendly operating systems (e.g., Windows NT™); and concomitant advances in **Advanced Continuous Simulation Language (ACSL)**[1] (e.g., Level 10) and **Modular Modeling System (MMS)**[2] (e.g., MMS for Windows) have brought many modeling applications within quick and easy reach of most people. Such applications include real-time models, **hardware-in-the-loop (HIL)** models, and large models, and produce significant savings in the cost and schedule time of typical projects. For example, with the high speed cpu and video, the degree of compromise in model detail necessary for real time performance has dropped; with ACSL Level 10, one can perform linear analysis and use the ACSL interface with MATLAB[3] for control algorithm design; and with MMS for Windows, one can construct a model and graphical user interface quickly and conveniently within a modest budget. MMS can be used to create simulation models, and with some changes, also stimulation models (i.e., HIL simulation models) which include actual control or protection system hardware.

Examples of recent applications of MMS are presented next. For new MMS users and those intending to join the MMS User Group, the procedure for creating and executing MMS models is reviewed following the examples.

EXAMPLES

Five applications are described here:

- A large model of a nuclear power plant for evaluating plant performance and planned plant enhancements
- Nuclear power plant model, called Power Master, used for digital control system design and preliminary HIL testing
- Evaluation of dynamic performance of U-tube steam generators with new operating and design parameters
- General stimulation model for control system development and training. Both analog and digital control systems can be included. Unlike the MMS simulation, the analog hardware does not lend itself to convenient and efficient initialization and freezing (i.e., hold). This shortcoming may be overcome by using replacement digital controller modules for replacing analog modules having integration functions ($\int$).

- On-line diagnostics

1. Large Model of a Nuclear Power Plant

A B&W plant is scheduled to be started up and brought on line in the near future and has some unique design features on the secondary side with respect to the steam generators, turbine, and feedwater heaters. The unique features include new design for steam generators and close coupling between the condensate and main feedwater systems. The secondary side may be upgraded based on experience with a similar power plant. An extensive MMS model (called **B&W Plant Model or BPM**) will be used to evaluate the planned enhancements to the performance of the steam, feedwater, and condensate systems; and certain concerns, such as the sensitivity of plant availability to secondary side upsets, proper functioning of the secondary system during transients, and proper functioning of the **Integrated Control System (ICS)**, which controls the nuclear steam system, in conjunction with the turbine control system.

Initially the BPM will be used to verify proper functioning of:

- the control algorithm
- the interface between ICS and turbine control system
- **balance-of-plant (BOP)** systems consisting of turbine extraction flow lines to **feedwater (FW)** heaters, **feedwater heaters (FWH)**, heater drain tanks, and FWH condensate flow paths

and for studying the effects of sensor, actuator, and **instrumentation & control (I&C)** cabinet power supply failures. The scope of the BPM includes: **(a)** the primary side (i.e., reactor, pressurizer, **reactor-coolant (RC)** pumps, **steam generators (SGs)**), **(b)** the secondary side (**low- and high-pressure (LP and HP)** FWH, FW pumps and valves, steam lines, steam safety and dump valves, HP and LP turbines, and electricity generator), and **(c)** logic for ICS, turbine control system, and BOP control.

The BPM may be modified later for real-time operation in closed loop with the plant control systems. Such an operation will facilitate checking the configuration of control modules before initial plant start-up -- significantly reducing cost and schedule time.

2. Power Master

Power Master is an MMS model of a B&W-designed nuclear power plant. This model was recently used for developing a digital replacement for the existing analog control system, ICS. The model was used in the simulation mode for developing advanced control algorithms and in the stimulation mode for verifying the correctness of configuring the Foxboro I/A Series hardware/software, the selected system, for implementing the advanced digital control algorithms (**Figure 1**). The scope of the model is slightly less than that of the BPM, in that the main turbines and condensate system are represented by boundary conditions. Since a digital control algorithm was to be developed, the control logic was included in the "discrete" section of the model, while the plant process model was included in the "derivative" section.

In the stimulation mode, the communication between the Power Master residing in the PC and the Foxboro system was achieved through a Foreign Device Gateway module and an RS-232 serial cable. Because of a more-than-expected communication delay, the sampling interval was too large to permit stable real-time closed-loop simulated plant operation without changing the control gain settings. However, since the verification of the control configuration was to be done with respect to transients run during the simulation phase, changing the gains was not a permissible option. The HIL simulation system was therefore time-scaled (i.e., slowed down until the sampling interval appeared fast relative to the process dynamics) to obtain transient responses comparable with the reference responses.

Other analog systems used on several B&W-designed nuclear power plants may be due for conversion to digital technology as spare parts to maintain the analog systems have become scarce and costly. The Power Master model is ideally suited for testing the digital replacements by stimulation.

3. Dynamic Analysis of Operation with SG Life Extension Strategy or SG Replacement

Utilities having **pressurized water reactors (PWRs)** with vertical **recirculating steam generators (RSGs)** have found that their SGs are expected to prematurely degrade or are already prematurely degraded. The utilities are therefore considering life extension strategies or replacement for the SGs. One of the life extension strategies is to lower the temperature of the reactor coolant entering the primary side of the SG (i.e., the hot leg temperature) to prolong tube integrity and make a corresponding adjustment in the steam pressure on the secondary side to ensure adequate heat transfer. The replacement SGs also typically employ reduced hot-leg temperature and have significantly different design characteristics (e.g., larger heat-transfer area and recirculation ratio, different secondary-side inventory distribution). Evaluation of dynamic performance of steam generators with new operating and design parameters can be performed using an MMS model[4]. The outcome of such an evaluation is the awareness of dynamic response characteristic of the steam generator and determination of changes necessary to the tunable parameters of the control system. An ideal way to determine tunable parameters is the HIL simulation approach. This approach also alleviates the proprietary concerns regarding transfer of control system information to a third party.

A similar dynamic analysis is also justified when a new nuclear fuel cycle (e.g., a switch from 12-month to 18-month fuel cycle) or a new fuel vendor is adopted, since the new fuel may have quite different reactivity coefficients and control rod worth than the one replaced.

4. Stimulation Model for Control Development and Training

A general PC-based HIL simulation constitutes an excellent platform for verifying field changes to existing control systems, developing new control systems or control system upgrades (e.g., analog to digital conversion), for developing man-machine interface, and for training I&C maintenance personnel in controller tuning. An example of such a system is a generic "feedwater/RSG/steam line" model stimulated by digital controller modules designed to replace the existing analog modules either on a one-for-one basis or with significantly increased functionality[5] **(Figure 2)**. The controller modules are **B&W Nuclear Technologies' (BWNT's)** STAR modules, which can replace analog modules, such as Bailey 721 or 820, or Westinghouse 7100 or 7300 series. The controller algorithm can be easily configured and changed using the graphics-based **Software Application Management System (SAMS)**, which translates the graphic logic diagram into a BASIC language code on a PC that can be edited before downloading into the controller EEPROM. An on-line monitoring and tuning PC can also be connected to the controller by an RS-232 cable to monitor the calculated output of each function block and to change the controller parameters.

The dynamics of the model in the example simulation make it an excellent choice for basic I&C training and control education in universities; not only does it include slow and fast dynamics, and non-linearities inherent in thermal-hydraulic phenomena, it also exhibits the not-so-common counter-intuitive response caused by the non-minimum phase characteristics of the SG level. That is, the recirculating steam generator has some of the zeroes of its transfer function in the right half s-plane. For example, when the steam flow is suddenly increased, the steam generator level rises initially (contrary to expectation), because of an increase in void, before dropping. The natural initial response to maintain SG level at its setpoint is to decrease feedwater flow, a wrong action. Thus, the example HIL simulation is an excellent candidate for using advanced theory, such as the **Quantitative Feedback Theory (QFT)**[6], and advanced design and analysis software tools, such as MATLAB. The control algorithm configured in the STAR modules encompasses a variety of control characteristics found in typical control applications. For example, it includes: loops with fast and slow dynamics, **proportional-integral-derivative (PID)** controllers, controller gain scheduling, feedforward, three-element level control, bumpless transfer between hand and auto modes, anti-reset windup, and low-pass filtering (i.e., first-order time lags). The control loops in this system were tuned by the Ziegler-Nichol's Ultimate Response Method[7].

In some applications, it is necessary to include analog control hardware in the loop. For example, if an analog control system is used in the plant, the analog HIL simulation will facilitate safe verification of intended control system field changes before they are implemented in the plant. Analog hardware-in-the-loop simulations are uncommon due to the difficulty of initializing and freezing the analog hardware. That is, while the MMS simulation model can be initialized readily at various power levels and frozen for debugging at any time, it takes considerable time and manual effort to do the same for the analog control systems. By using the STAR modules in conjunction with the analog control system, it seems feasible to automatically initialize and freeze the control system. For example, the STAR modules can be used to replace analog modules that include integrators, thereby allowing the integrators in the STAR modules to be initialized at any predetermined value by using a digital input (switch initiator signal) and an analog input (power level).

5. On-Line Diagnostics

The real-time HIL models developed in various applications can also be executed on-line to compare the actual plant responses with those predicted by the model. If and when the two show statistically significant difference, a change in the plant characteristic, or a malfunction, or operation of the plant outside the range of the model is indicated. Based on the nature of the difference, a more in-depth localized investigation can be initiated.

HOW MMS SIMULATION AND STIMULATION MODELS ARE CREATED?

Simulation is the all-software system used initially for process or control algorithm and strategy design, while **stimulation** is the hardware-software system used for hardware development and testing. The MMS includes both of these approaches. Together, these approaches constitute a cost-effective way of developing a process or control system including the planning for initial start-up. A substantial part of what formerly was done in the field during initial start-up can now be done in the office using stimulation, thus producing significant reductions in the cost and schedule time of the project.

Simulation

To develop a simulation efficiently, three steps are commonly used in the MMS:

- Pre-processing for model development
- Model execution and use of tools, such as MATLAB, for analysis and optimization. A graphical user interface may also be created to enhance the efficiency and effectiveness of simulation.
- Post-processing for documenting simulation results

Pre-processing

Pre-processing is a step performed on a PC using the MMS Model Builder®, which operates under Microsoft Windows™, for interconnecting icons (i.e., graphic entities) from a library to represent the system or process being modeled (e.g., **Figure 3**). Associated with each icon are:

- a macro, written in ACSL, that includes **pre-engineered and validated**, and therefore reliable, set of first-principles equations describing the dynamic behavior of the component represented by the icon in terms of conservation of mass, energy, and momentum; heat transfer; pressure drop; etc. ACSL is a high-level language featuring sorting for correct calculation sequence, translation into FORTRAN with the ACSL translator, and a choice of integration algorithms at run time.

- a program to calculate the parameters associated with a component (i.e., coefficients of the equations) from its design and operating data.

- interconnection ports and type (e.g., inlet/outlet, resistive or capacitive) that permit one icon to be connected with another to represent the desired system.

Once icons are selected and interconnected, the operating and physical data (in US or SI units) are entered in user friendly forms (e.g., **Figure 4**). The model is then automatically developed. This automated model building system accelerates the initial development of, and subsequent changes to, the model. Since MMS is an open architecture system, a user can include custom ACSL code and FORTRAN or C routines in the model. Examples of custom routines are: routines for graphical user interface featuring trends, schematic, and keyboard or mouse interaction; and communication with external hardware, such as control systems. A stand-alone graphical user interface can also be created in the Windows environment and connected to the model variables using a **dynamic digital exchange (DDE)** interface. Figures 3 and 4 relate to the BPM in Example 1.

The outcome of the pre-processing step is a model comprising an ACSL source file, a FORTRAN file, an object file, and an executable file. The ACSL source file has a "derivative" section for continuous processes and analog control logic, and a "discrete" section for discrete (i.e., sampled) processes and digital control logic. Although commands can be typed at model run-time, a command file is usually prepared to include frequently used commands and command macros.

Execution

The model can be executed in several ways. Forcing functions can be changed to determine the process response. The evolution of response during model execution can be seen by using either a custom graphical user interface or ACSL/PC for Windows™ interface. Parameters can be changed to test the effect of changing process or control characteristics, or failing a sensor or an actuator. During the design phase, the process or control parameters can be optimized by using an optimization procedure. After the process is built, the model parameters can be optimized to match the as-built system response.

Linear analysis can be performed to obtain the simulated system attributes, such as: linearized model, poles (eigenvalues) and zeros of the transfer function, Nichols chart, Nyquist and Inverse Nyquist plots, root locus, and bode plots; and the analysis results can be seen on the graphical interface. A linearized model of the process can also be input to MATLAB for further analysis and control algorithm development. As an example of linear analysis capability, **Figure 5** shows the variation of the largest-magnitude eigenvalue (i.e., the smallest time constant) of the NSS model in Example 1 with power level. Such analysis is necessary to determine the time step for fixed-step integration algorithms.

The database of the model (i.e., values of all model variables) can be saved as initial condition for starting the model with the same values at any subsequent time.

The numerical integration algorithm can be selected from a choice of nine algorithms that include fixed-step/fixed-order (e.g., Runge-Kutta 1st, 2nd, and 4th order), variable-step/fixed-order (e.g., Runge-Kutta-Fehlberg 2nd and 5th order), and variable-step/variable-order (e.g., Adams-Moulton and Gear's stiff) algorithms.

The model output is displayed on the screen and stored in files for subsequent viewing and analysis. Display options include values of variables selected at run-time, plots of variables (**Figure 6**), and trends on a graphical user interface as a transient evolves (**Figure 7**). In fact, Figure 5 relates to the tuning of main FW valve control loop in Example 4. The values of Ultimate Gain (UG) and Ultimate Period (UP) were: UG = 1.35, UP = 10 sec/(1.8 cycles x 60 sec/min) = 0.0926 min. For the controller equation: output = K_p * error + $K_i \int$ (error*Dt), K_p = 0.45xUG = 0.6075, and K_i = UG/(UP/1.2) = 7.87 repeats/min.

Post-processing

A log of the terminal activity during a simulation run is saved in one of the model output files in the ASCII format. Another output file is a record (in compressed format) of the time-history of model variables selected at run time. While these variables can be plotted in several ways during run-time, they can also be plotted after the run by retrieving information from the time-history file. While default values exist for most execution-time choices, the user can change the default values to suit a particular application. For example, any variable can be selected as the independent variable (x axis); up to five variables can be plotted in different colors on the y axis; and scales and ranges can be customized (e.g., log-linear scale, expanded x and y axis ranges). These features are quite useful for analysis and documentation of the model and responses.

Stimulation

Stimulation models are real-time models used for developing hardware-software systems, such as control systems. They are derived from simulation models by removing the calculations that are to be replaced by the stimulation equipment (e.g., control system), adding communication software for linking with the stimulation equipment, and modifying some of the model calculations to permit the use of fixed time-step integration algorithms, such as Runge-Kutta. The simulation model in conjunction with the stimulating system is called HIL simulation. The communication software includes a driver routine that uses a usually vendor-supplied library, such as: **(a)** Bailey Controls' **Communication Interface Unit (CIU)** software that passes data over a serial or parallel data highway, and **(b)** Keithley Metrabyte software that sends and receives data through analog and digital input/output cards, which can be mounted in the PC expansion slots. Modification of model calculations includes separation of fast and slow dynamics for integration with different time-steps, replacement of some fast dynamics with imbedded iterative or steady-state solutions, and simplifications. Common features of simulators, such as Initialize and Hold (also called Freeze), can be added to an HIL simulation system.

OPTIONS FOR DEVELOPING MMS MODELS

Several options, ranging from a pre-developed specific model to a complete modeling system, exist for developing a dynamic simulation model. These options serve to accommodate variations in model application scope, manpower availability, schedule requirements, and concern for providing proprietary plant or process data to a third party. These options include:

- **Pre-built plant-specific model:** This option is suitable when in-house personnel with modeling background are not available, or schedule constraints require a third party to develop the model. With this option, it is necessary to provide pertinent design and operating information to the third-party model developers.

- **Pre-built plant-specific model with tools for recalculating parameters:** This option helps to accommodate a tight schedule for the model, while providing a cost-effective way for long-term changes in model parameters to represent **a)** changes in the plant equipment, such as crud buildup and tube plugging in steam generators, and **b)** a similar plant with different rating and component characteristics (e.g., valve characteristic and flow conductance, pump head-flow curve).

- **Generic plant model with tools for calculating parameters for a specific plant:** This option is suitable when manpower is limited and there is concern about the transfer of proprietary information to a third party.

- **Complete modular modeling system to build plant models:** This option is suitable for a long-term, continuing use of the modeling system by in-house personnel.

CONCLUSION

With the recent and ongoing advancement in PC hardware and software technology and the MMS, models of a power plant can be developed quickly and inexpensively. MMS and related engineering services offer many options for developing the models, from do-it-yourself to turnkey models. The usefulness of modeling in a project is real and pays for itself quickly. As pointed out in a recent article[9], the overall project schedule and cost can be reduced if start-up planning is done early in a project. In our opinion, including simulation and stimulation in start-up planning will not only provide valuable feedback during the design phase and contribute to a short and smooth start-up, but will also reduce the risk of unforeseen developments during start-up.

REFERENCES

1. ACSL Reference Manual. Mitchell & Gauthier Associates, 200 Baker Avenue, Concord, Mass. 01742-2100, USA, 1991.
2. MMS Theory and User Manuals. B&W Nuclear Technologies, P. O. Box 10935, Lynchburg, VA, USA 24506-0935, 1993.
3. MATLAB. The Math Works, Inc, 24 Prime Park Way, Natick, MA 01760, USA.
4. "Low-Cost/Risk Approach for Verifying Modifications to Dynamic Plant Operation and Instrumentation & Control System Resulting from Steam Generator Replacement," S. S. Godbole and G. F. Malan, 4th International Conference on Simulation Methods in Nuclear Engineering, Montreal, Canada, June 2-4, 1993.
5. "A Hardware-in-the-Loop PC-Based System for Developing & Tuning Control Algorithms and Training," S.S. Godbole, 1993 ISA International Conference, Chicago, September 20-23, 1993.
6. Quantitative Feedback Theory (QFT), Vol. 1, Isaac Horowitz, QFT Publications, 4470 Grinnell Ave., Boulder, Colorado, 80303.
7. Reference Guide to PID Tuning. Control Engineering, Cahners Reprint Services, 1350 E. Touhy Ave., Des Plaines, IL 60018, USA.
8. MMS Model Builder Users Guide. B&W Nuclear Technologies, P. O. Box 10935, Lynchburg, VA, USA 24506-0935, 1993.
9. Robert E. Follett, "Power plant start-up demands productive methods and practices," Power Engineering, May 1993.

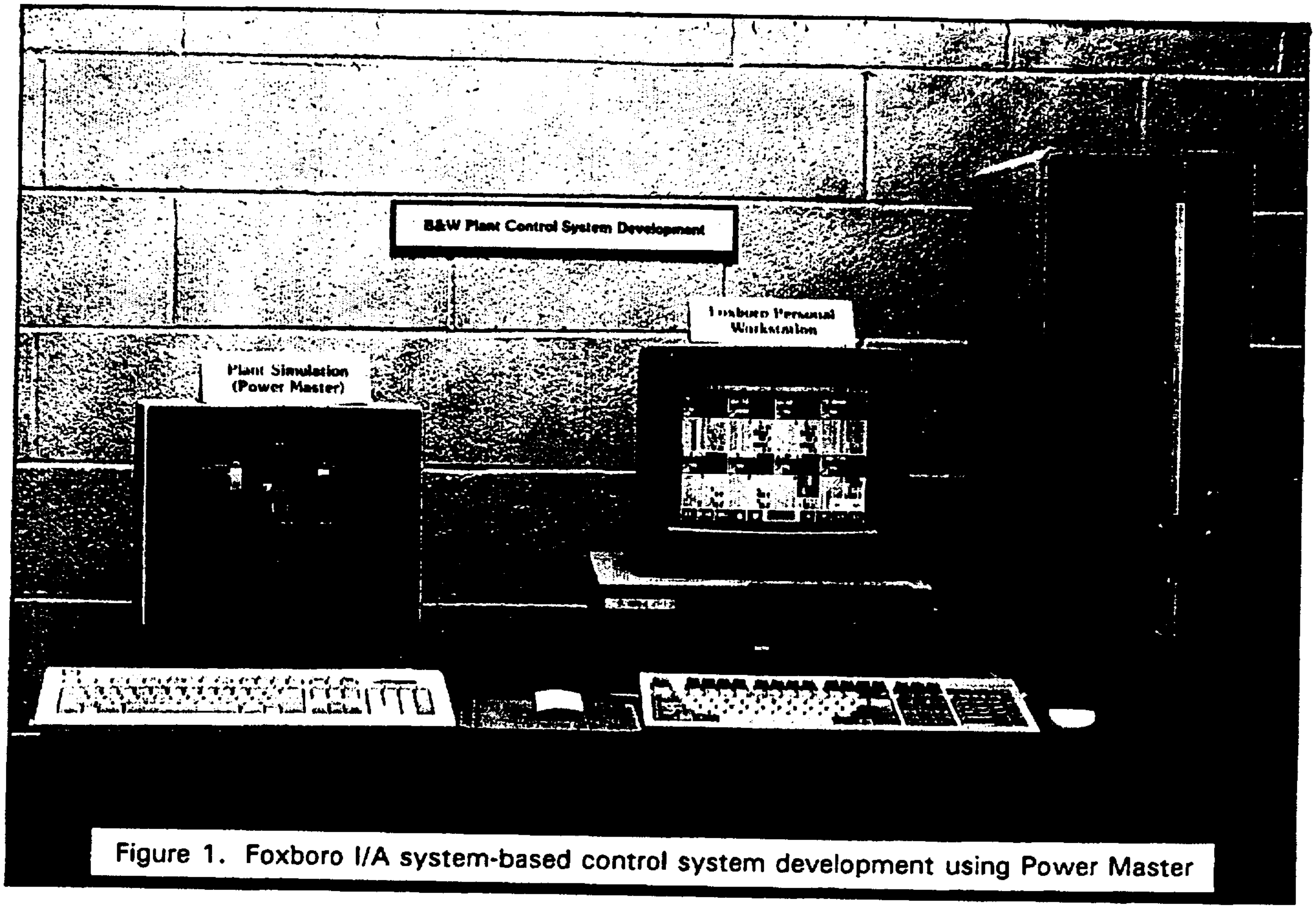


Figure 1. Foxboro I/A system-based control system development using Power Master

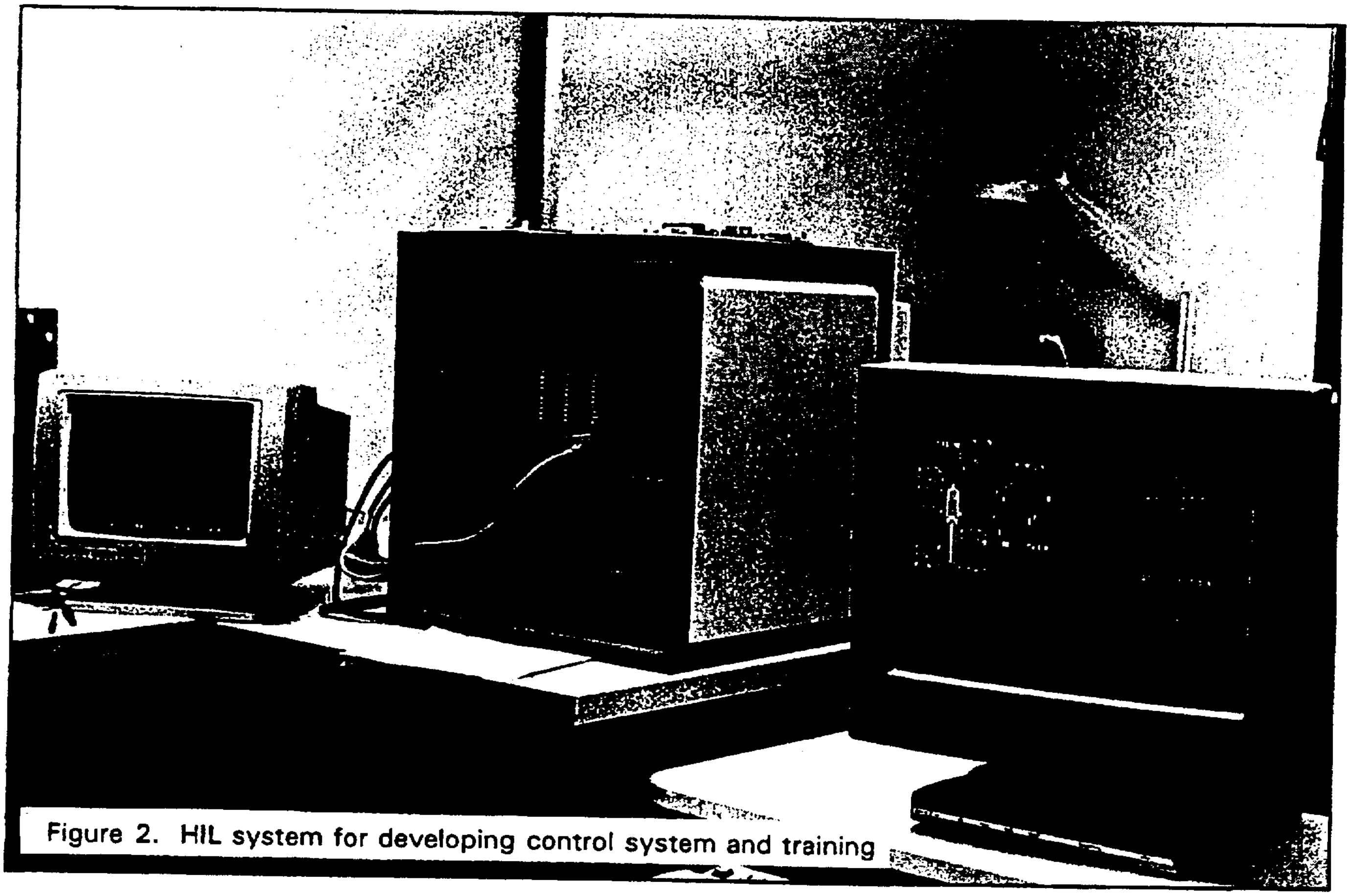


Figure 2. HIL system for developing control system and training

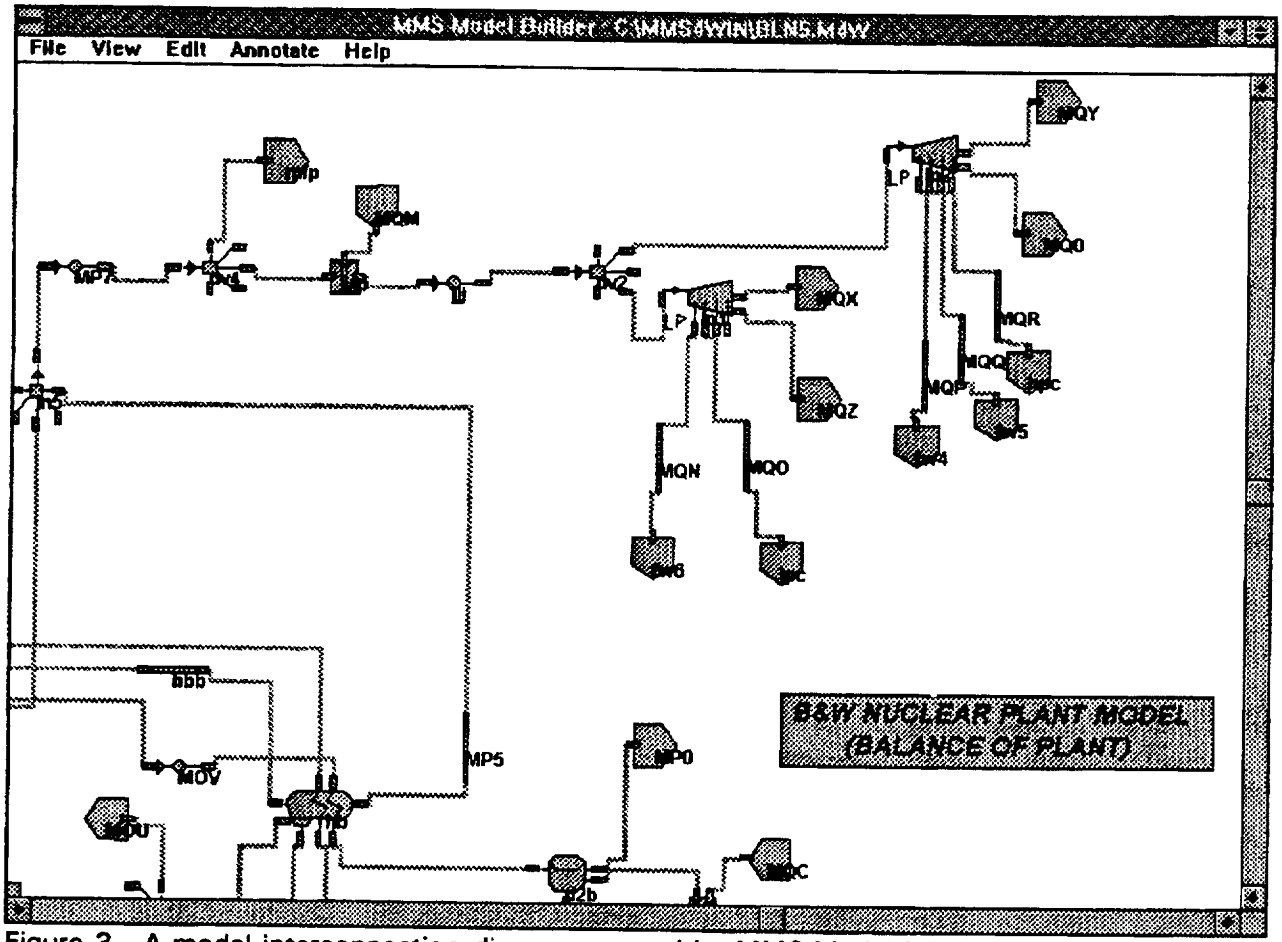
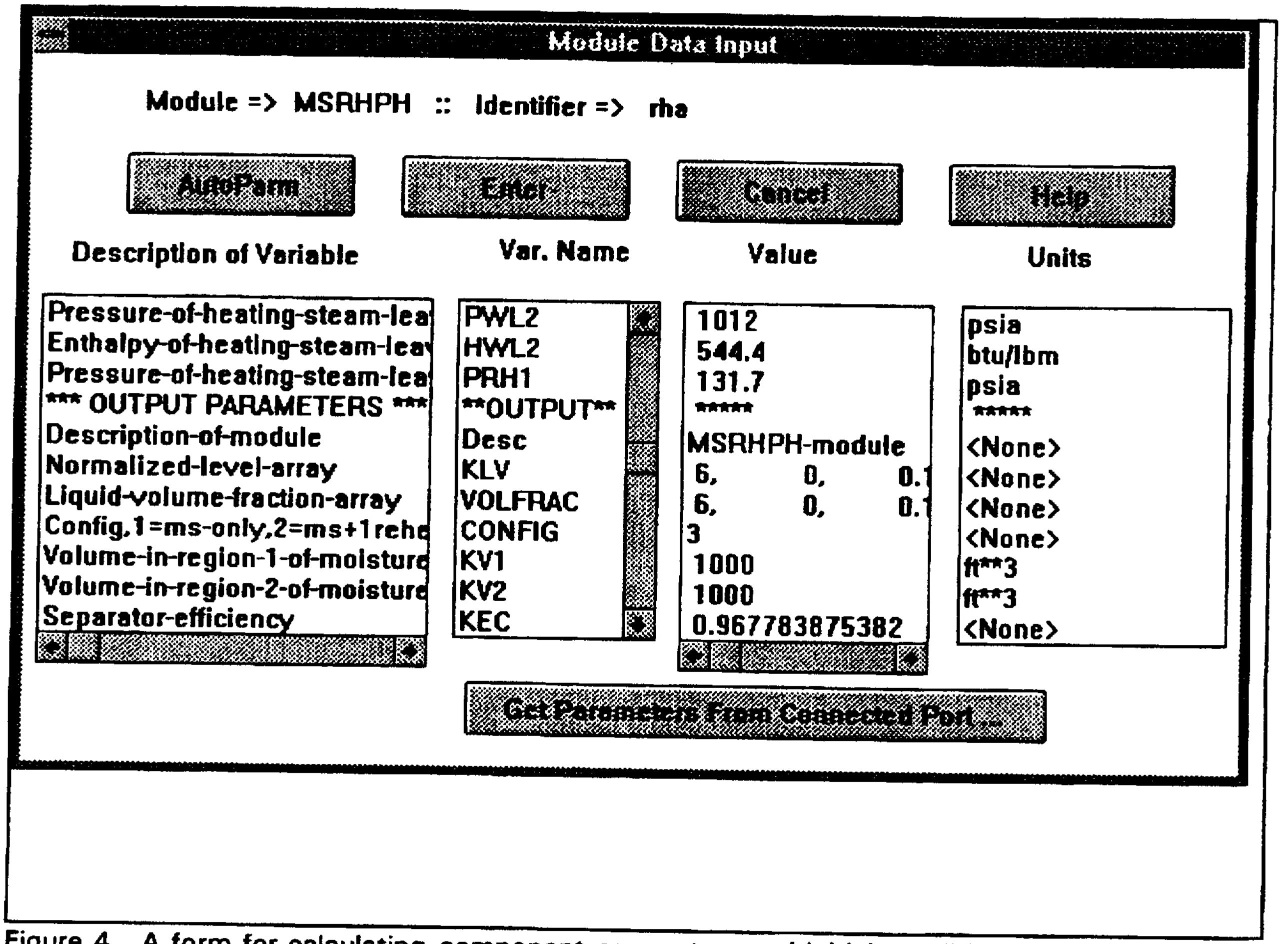


Figure 3. A model interconnection diagram created by MMS Model Builder

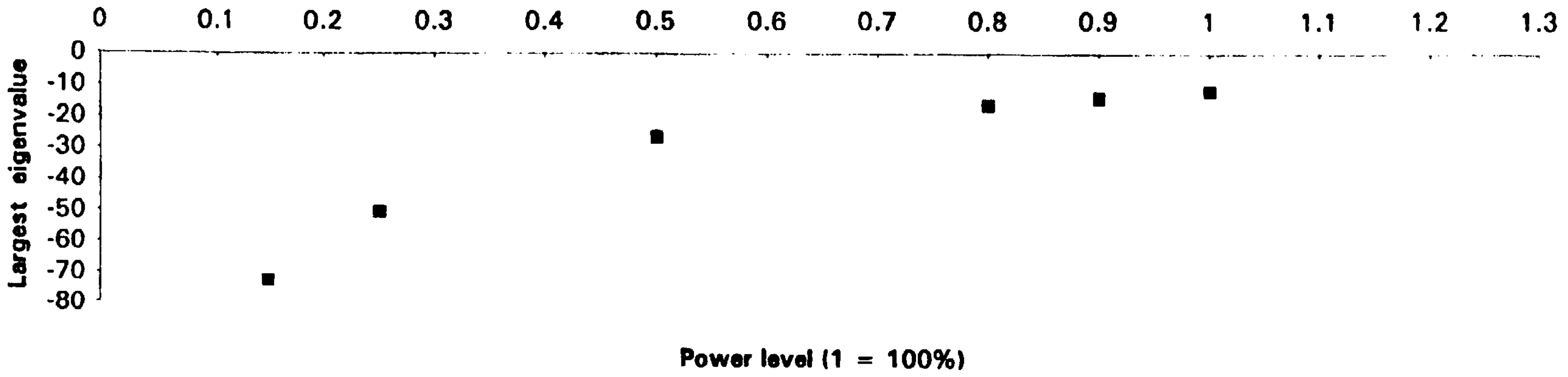


Module => MSRHPH :: Identifier => rha

Description of Variable	Var. Name	Value	Units
Pressure-of-heating-steam-lea	PWL2	1012	psia
Enthalpy-of-heating-steam-lea	HWL2	544.4	btu/lbm
Pressure-of-heating-steam-lea	PRH1	131.7	psia
*** OUTPUT PARAMETERS ***	**OUTPUT**	*****	*****
Description-of-module	Desc	MSRHPH-module	<None>
Normalized-level-array	KLV	6, 0, 0.1	<None>
Liquid-volume-fraction-array	VOLFRAC	6, 0, 0.1	<None>
Config,1=ms-only,2=ms+1rehe	CONFIG	3	<None>
Volume-in-region-1-of-moisture	KV1	1000	ft**3
Volume-in-region-2-of-moisture	KV2	1000	ft**3
Separator-efficiency	KEC	0.967783875382	<None>

Figure 4. A form for calculating component parameters and initial conditions

Figure 5 . Variation of largest eigenvalue (i.e., fastest timeconstant) with power



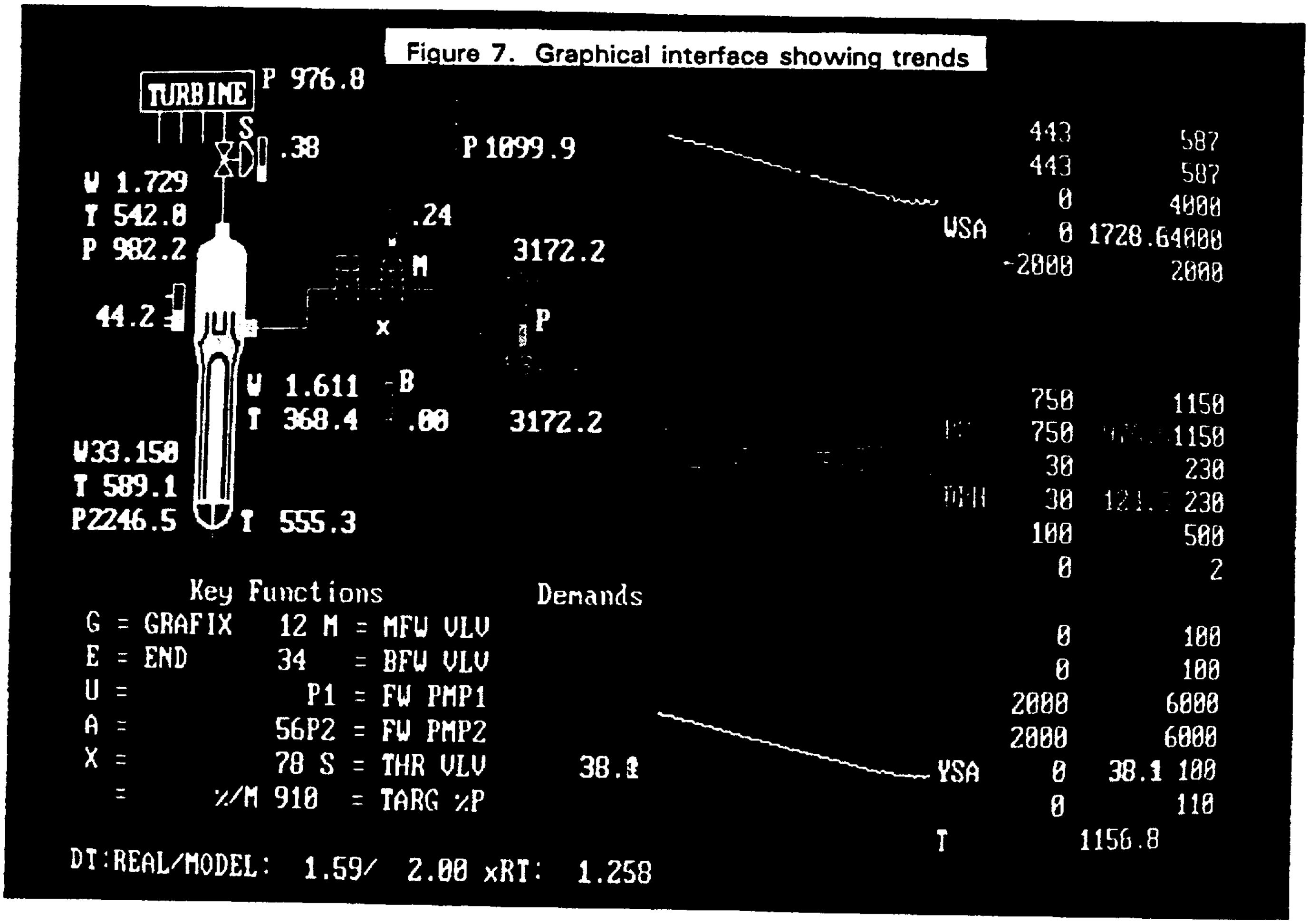


Figure 7. Graphical interface showing trends

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TURBINE   P 976.8
            S
             .38            P 1099.9                    443        587
V 1.729                                                 443        587
T 542.0               .24                                 0       4000
P 982.2                                          VSA      0 1720.64000
                      M        3172.2                 -2000       2000
44.2
                   x            P

      V 1.611    B                                      750       1150
      T 368.4     .00         3172.2                    750       1150
V33.150                                                  30        230
T 589.1                                                  30 121.   230
P2246.5       T  555.3                                  100        500
                                                          0          2
      Key Functions          Demands
G = GRAFIX    12 M = MFW VLV                              0        100
E = END       34   = BFW VLV                              0        100
U =              P1 = FW PMP1                          2000       6000
A =           56P2 = FW PMP2                           2000       6000
X =           78 S = THR VLV         38.1       YSA       0   38.1 100
  =       %/M 910  = TARG %P                              0        110
                                                 T        1156.8
DT:REAL/MODEL:  1.59/  2.00 xRT:  1.258
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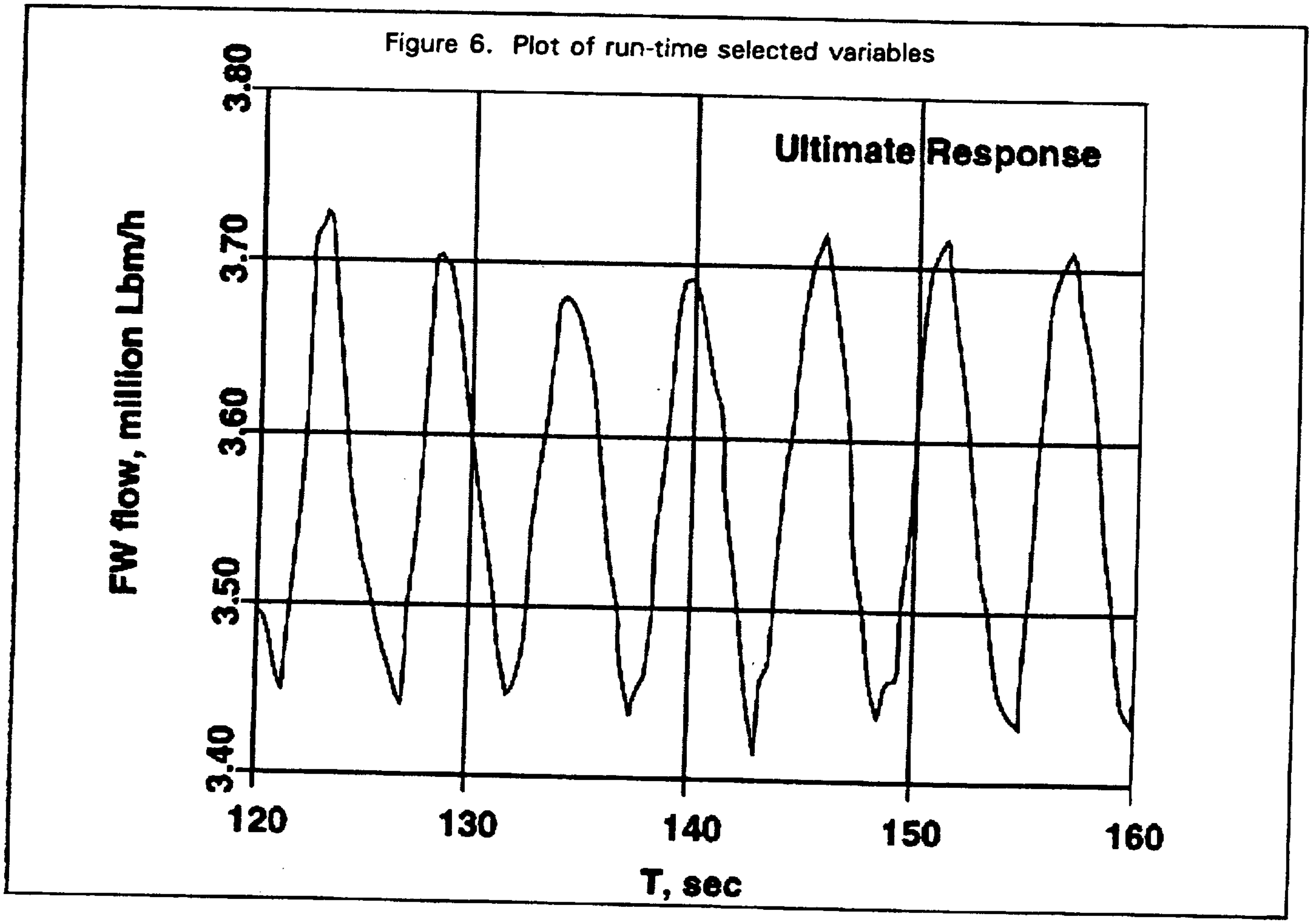

Figure 6. Plot of run-time selected variables