COMBINED RESEARCH AND CURRICULUM DEVELOPMENT FOR POWER PLANT INTELLIGENT DISTRIBUTED CONTROL

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ABSTRACT

An NSF combined research and curriculum development project was conducted from 1992 to 1996. New graduate courses on 1) Power Plant Dynamics and Control and 2) Power Plant Intelligent Distributed Control were developed and presented. The capstone course Power Plant Intelligent Distributed Control covered advanced subjects and laboratory experiments developed in the research portion of the project including: 1) extensions to achieve real-time performance of large scale power plant simulations using UNIX network programming, 2) distributed implementation of advanced controller programming in an architecture of workstation and microprocessor-based controllers, and 3) intelligent control using fuzzy logic, neural network, genetic algorithm, and reconfigurable control techniques. After the presentation of a curriculum development update, a summary of research activities is presented to complete overview of the project results.

BACKGROUND

The background for this three year research and curriculum development project was obtained by the successful completion of two major projects initiated in 1989. A 1989 NSF equipment grant (ECS-8905917)[1] was used to establish the Intelligent Distributed Controls Research Laboratory (IDCRL) through the acquisition of a commercial microprocessor-based control system.[2] The laboratory was used to develop advanced control experiments in a major DOE project, "Intelligent Distributed Control for Nuclear Power Plants", DEFG-89ER12889. The research activities of the DOE project culminated in an actual in-plant experiment conducted on April 1, 1993 that demonstrated fault-accommodating characteristics which can be obtained by intelligent control applications.[3,4] The 1989 NSF supplied commercial-grade microprocessor-based controllers were also used in a prototype experiment at the Penn State TRIGA reactor[5] and led to an NSF/EPRI Intelligent Control Initiative Project conducted from 1993 to 1996, "Experimental Development of Power Reactor Intelligent Control", NSF ECS-9216504/EPRI RP8030-04.[6]

The 1992 combined research and curriculum development project was formulated to efficiently transfer the many new specialized skills developed in the prior NSF and DOE projects to a next generation of student researchers. A motivation for continued research in advanced control techniques for application to power plants and power systems is that there is substantial industry efforts to upgrade Instrumentation and Control at existing U.S. power plants, both fossil and nuclear. These upgrades are economically justified to improve the reliability, economy and safety of existing plants in the face of difficulties in pursuing new construction within recent years. In addition to developing new curriculum to train the engineers for the industry I&C modernization program, an expanded research objective was intelligent control at supervisory and plant-wide coordination levels.

INTELLIGENT DISTRIBUTED CONTROLS RESEARCH LABORATORY

A major planned expenditure in the first year of the project was the expansion of the IDCRL to support course instruction as well as provide enhanced research capability. The Unix network expansion was completed with the addition of four Sun Spare Workstations. Mitchell and Gauthier's Advanced Continuous Simulation Language (ACSL) and Mathworks Simulink/Matlab software were also installed in the Unix network. A commercial-grade multifunction controller and PC computer were acquired to expand microprocessor-based controller programming capability. The Simulink/Matlab software package was immediately used to support an established Nuclear Engineering (NucE) reactor control course, NUCE 505 in Spring 1993, and an Electrical Engineering (EE) power engineering course, EE 556 in Spring 1994. Previous experience with the software enabled the rapid utilization of the newly installed Unix network. The PC version of Matlab had been previously integrated over several years into the control course. Experience with the nonlinear simulation capability of the Simulink software on Macintosh computers was first obtained in the Fall 1992 offering of the NUCE undergraduate reactor experiments laboratory course, NUCE451.7 Later in the Spring 1994, the PC version of Simulink/Matlab was also integrated into the power engineering course in developing a Power Systems Toolbox for the EE power engineering course, EE 461.

From a research standpoint, the laboratory expansion was essential to better achieve real-time execution of distributed simulation of plant-wide power plant systems. Prior to the expansion, the distributed simulation was implemented on general purpose Vax mainframe computers with coordination through a Unix workstation. The general purpose Vax computers are used for a variety of College of Engineering research and courses. It was thus difficult to command enough priority to always obtain real-time performance when a large number of other users were on the system. Priorities on the expanded IDCRL can be scheduled as required to achieve desired levels of real-time performance. And, the newer technology of the Spare computers offers better performance than the Vax 8550 mainframes. Since the previous distributed simulation system was deployed on a Vax VMS platform, our real-time extensions of the Modular Modeling System needed to be converted to the Unix platform. The major portion of the conversion centered around the TCP/IP communication to the coordination computer. Additional software for communication directly between a Spare computer and Bailey microprocessor-based computer was also converted from a Concurrent Unix platform.

CURRICULUM DEVELOPMENT

Our 1995 ASEE paper[8] emphasized the early curriculum development of the project, and this paper emphasizes the final development. Two new graduate level courses were developed and conducted.

The "Power Plant Dynamics and Control" course (EE/NucE 597E) was conducted in the Fall 1994 as a first year graduate course. The principal objective of the course was to develop the basic modeling and dynamical simulation of a complete fossil power plant including the fossil-fueled steam supply, turbine-generator, and feedwater systems. Table I summarizes subjects covered and actual time spent on each topic.

Table I: Subjects Studied in Power Plant Dynamics and Control.

3 weeks	Conservation of mass, momentum, and energy, thermal-hydraulics and heat transfer.
1 week	Review of Simulation Methods
2 weeks	Introduction to the ACSL Macro language and B&W Modular Modeling System
2 weeks	Drum boiler modeling, simulation, dynamics and control
2 weeks	Addition of economizer, superheaters and reheater.
4 weeks	Addition of turbines and generator

The approach adopted in our research and this course is to utilize the B&W Modular Modeling System (MMS). The MMS was originally developed as an Electric Power Research Institute sponsored project.[9] It uses the Macro feature of the ACSL language to provide a library representing all components of power plants. An ACSL Macro is analogous to a Fortran subroutine in that it allows for organization of a large simulation into smaller and more manageable parts. It differs in that each invocation of a Macro instantiates unique Fortran statements for a specific power plant component. The user needs to understand the component modeling, specify a unique name, and supply the parameters required to characterize a specific component. The structure and function of ACSL Macro programming was demonstrated by implementing the pipe three-equation set as a Macro.

The "Power Plant Intelligent Distributed Control Course" (EE/NucE 5971) was conducted in the Spring 1995 as an upper level graduate course. It was designed to prepare new students to continue and expand upon the research completed during the first two years of the project. This course had two major instructional focus areas: 1) the architecture and function of intelligent systems, and 2) implementation for plant-wide automation of power plants using distributed systems programming. Table II summarizes the subjects covered and time allotted to each.

Table II: Subjects Studied in Power Plant Intelligent Distributed Control.

2 weeks	Overview of intelligent control systems
2 weeks	Artificial neural network controller design
2 weeks	Fuzzy logic controller design
2 weeks	Advanced controller design: optimal, LQG/LTR and robust control
1 week	Controller design by genetic algorithm
1 week	Introduction to computer architectures and Unix
4 weeks	Unix network programming
1 week	Implementation of distributed simulation and control.

The initial introduction started with the overview of intelligent control systems. A power plant is a large-scale complex system with high degree of nonlinearities, a large number of variables and numerous components. Therefore, conventional controls alone are inadequate to achieve maximum possible reliability and economic performance. Intelligent control techniques are to give human like intelligence to controls when plants are complex, uncertain, and changing constantly for various operating conditions. An intelligent control system is in the form of an hierarchical structure with several layers of controls with different levels of intelligence. Low level control involves tight controls with sensors and actuators where conventional control techniques such as PID, optimal and robust controllers can be used. As the level goes up, controllers require increased intelligence but less precision. Throughout the semester, four basic techniques of intelligent control were presented: artificial neural networks, fuzzy logic control, genetic algorithm, and expert systems.

Instruction on distributed systems programming included the specific tools required for implementing and testing research concepts in the Penn State Intelligent Distributed Controls Research Laboratory. Here several networked SPARC workstations provide the capability for real-time distributed simulation including hardware-in-the-loop testing of low level control algorithms executed in actual power plant distributed control system hardware. For hardware-in-the-loop testing, simulated plant parameters are transferred to the inputs of the low level control algorithms and the controller response is returned to stimulate the simulation. The tools required for conducting research in this environment are related to Unix network programming and our extensions to the Modular Modeling System that enable real-time simulation of plant-wide power plant systems.

RESEARCH

The curriculum development significantly benefited from research conducted as part of the project, There is often overlapping technical areas in a particular research work; but for the purpose of organizing the overview, the areas are categorized as: 1) distributed simulation research 2) model-based control algorithm research, 3) fuzzy logic control, 4) neural network control, 5) applications of genetic algorithms, 6) applications to power system control, 7) applications to fossil power plants, and 8) applications to nuclear plants,

Distributed Simulation Research: The need for distributed simulation research was motivated by the desire to expand previous intelligent control research to plant wide control. Plant-wide distributed real-time simulation of both nuclear and fossil power plants was developed for a network of Unix workstations. 10-12 The most recent development provides a plant-wide simulation of the PECO (Philadelphia Electric Company) Cromby No. 2. unit.[12] The boiler, turbine-generator, feedwater and condensate systems are organized for simulation on different workstations and are coordinated to real-time execution through a centralized plant data base and distributed simulation manager, Figure 1. The Cromby unit boiler utilizes a split furnace arrangement with superheat and reheat. Other components of the boiler system model include the economizer, attemperators, and three element PID controllers for drum level control and steam temperature attemperation. The turbine generator system model includes both high and low pressure turbines and are coupled to a synchronous generator modeled using nonlinear flux linkage equations. The feedwater system model represents two stages of regenerative heating in two parallel paths. The condensate system includes the condenser and four stages of feedwater heating in a single path. The distributed simulation results were validated against available plant transient data.

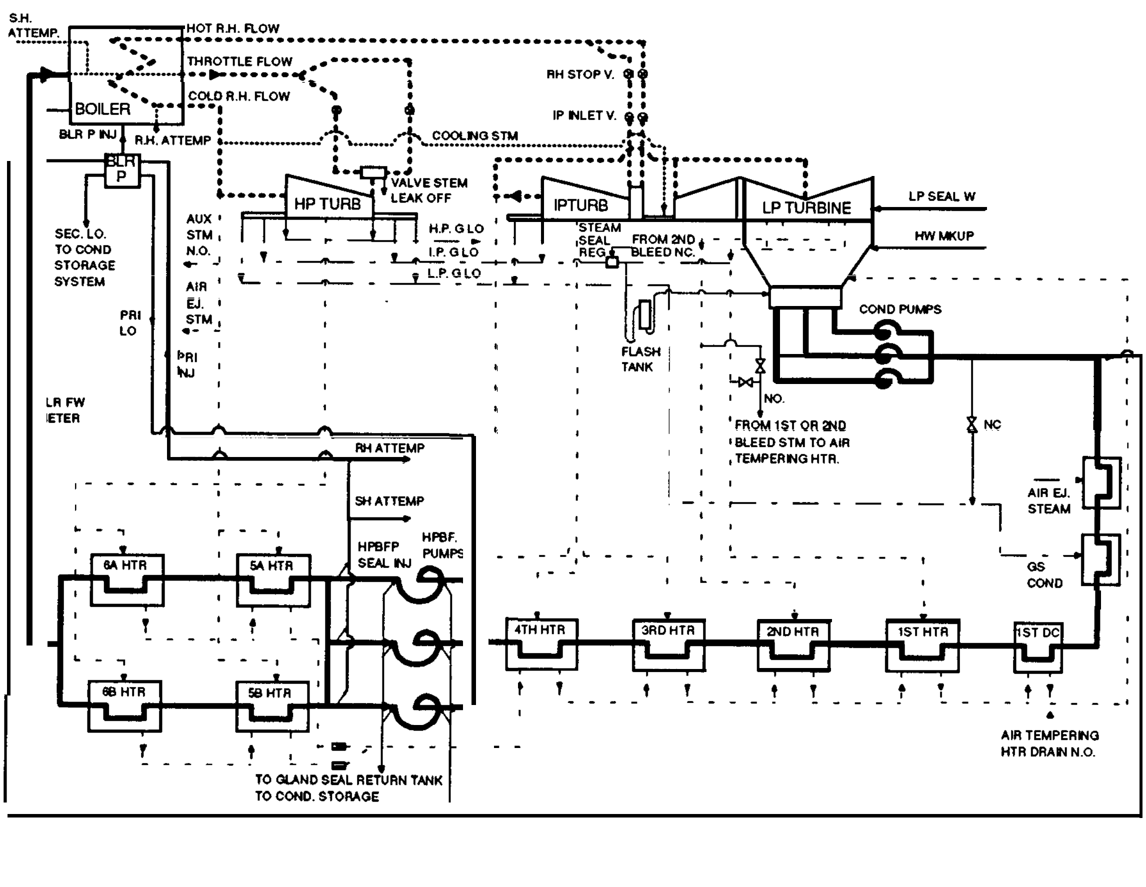

Figure 1, Distributed Simulation Setup.

Model-Based Control Algorithm Research: Research into applications of optimal and robust control algorithms for power plants was performed in order to formulate the best possible local subsystem controls as part of an intelligent control structure for a large scale system. A cogeneration plant, [13] which supplies electricity and steam to an industrial process plant, often experiences considerable variations in the power system frequency and extraction steam pressure due to external disturbances such as abrupt change in electrical and steam loads. A robust multi-input multi-output (MIMO) controller using the Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR) was developed for a cogeneration plant, Figure 2. In this case, the robust LQG/LTR controller is designed to provide an auxiliary control input to a cogenerator with classical PID controllers. Results demonstrate that the LQG/LTR controller significantly improves the performance of the frequency and extraction steam pressure against abrupt changes in load. Analogous local optimal and robust control was studied for nuclear power plant subsystems.'4

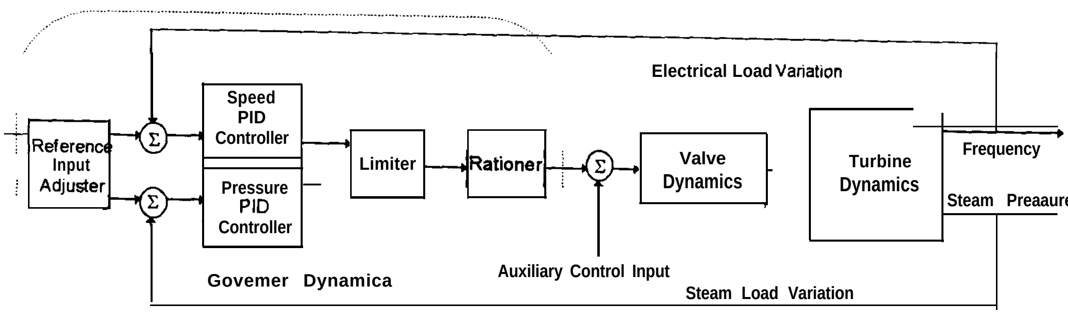

Figure 2. Block Diagram of a cogeneration plant.

Fuzzv Logic Control: Although our research involving fuzzy logic control is best framed with a particular power plant application, some research results for self-organization of a fuzzy controller were obtained for general control applications. [15-16] Controllers designed on the basis of a mathematical description and its linearized model can be difficult to implement on some real systems. For fuzzy logic control, the most important task is to form the rule base which represents the experience and intuition of human experts. For the case where a rule base of human experts is not available, the Fuzzy Auto Regressive Moving Average (FARMA) procedure was developed, Figure 3.

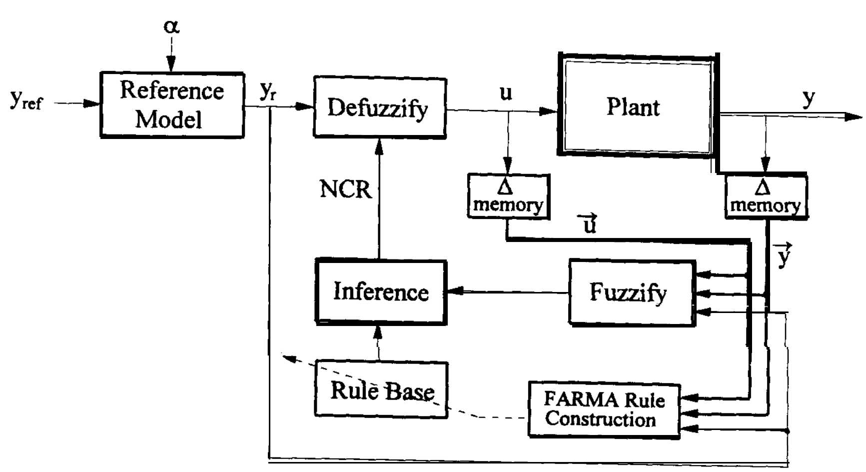

Figure 3. The FARMA control system architecture.

Neural Network Control: Several research efforts of a general nature produced significant results. One area is the utilization of diagonal recurrent neural networks (DRNN) for dynamic systems control.[17,18] The architecture of DRNN, Figure 4, is a modified model of the fully connected recurrent neural network with one hidden layer, which is comprised of self-recurrent neurons. Two DRNN's are utilized in a control system: diagonal recurrent neuroidentifier (DRNI) and diagonal recurrent neurocontroller (DRNC). A controlled plant is identified by the DRNI, which then provides the sensitivity information of the plant to the DRNC. A generalized dynamic back propagation algorithm (DBP) is developed and used to train both DRNC and DRNI. Due to recurrence, the DRNN can capture the dynamic behavior of the system. To guarantee convergence and for faster learning, an approach that uses adaptive learning rates was developed. Convergence theorems for the adaptive backpropagation algorithms were developed for both the DRNI and DRNC. The DRNN was shown to have dynamic mapping characteristics and to require fewer weights when compared with a fully recurrent neural network. Other related research in neural network theory incorporated concepts from robust control theory[19,20] and the utilization of multiple layer neural networks in optimal tracking and decentralized control .2* 722

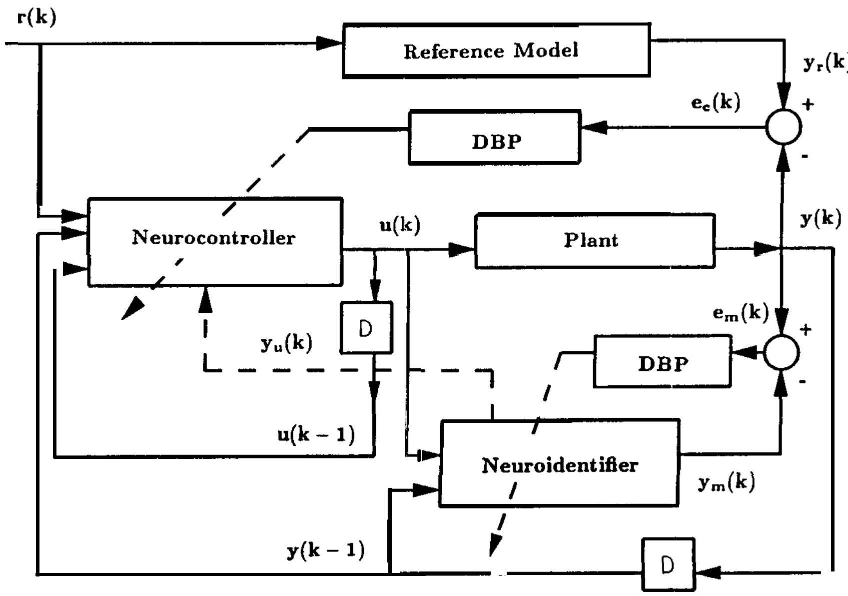

Figure 4. Block diagram of DRNN based control System,

Applications of Genetic Algorithms: Similar to training performed in neural network applications, genetic algorithms have been examined for tuning of power plant controls. In the genetic algorithm approach, an initial random population of binary strings is created. Each of the strings represents a possible solution to a search problem. The strings are converted to decimal equivalents of a candidate solution to a control problem. The fitness of each candidate is tested in the environment and evaluated through an appropriate measure. The algorithm is driven towards maximizing this fitness measure. If a termination condition is not met, three genetic operations of reproduction, crossover, and mutation are invoked to create a new population. In reproduction, a portion of the new population of strings are generated that reflect the fitness of the previous generation's fit characteristics. In crossover, two strings are selected from the population at random and a random position in the strings is replaced. In mutation, a random string is selected and a random bit position changed. The genetic algorithm was used to design LQR controller and for tuning of PI controllers applied to a multivariable boiler controller design and included coupling gains between three single loop controllers.[23] In a second application, feedforward control signals were also determined for a nuclear power plant steam generator.[24]

Applications To Power Systems: Both fuzzy logic and neural networks were studied for power system applications. Many kinds of stabilizers have been proposed to improve the stability of synchronous generators, Figure 5. The gain settings of power system stabilizers (PSS) are usually fixed at a certain set of values which are determined based on a nominal operating point. It is impossible for these fixed gain stabilizers to maintain the best darnping performance when there is a drastic change in system operating condition, Traditionally, these controllers are designed on the basis of a mathematical description of a generator and its linearized model. Therefore, it is difficult to implement these model-based controllers to a real system, especially to a system which is complex and nonlinear. In one alternative, the Fuzzy Auto-Regressive Moving Average (FARMA) controller was applied.[25-27] Better performance than conventional PSS was demonstrated in simulations with normal and heavy loads, isolation of a transmission line, and different inertia constants for the synchronous generator. Neural networks were also shown to have similar potential for performance improvement over conventional model-based approaches.[28-31]

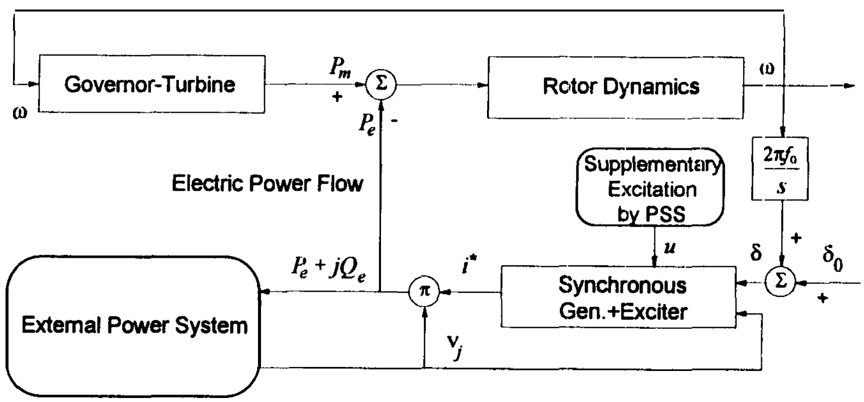

Figure 5. A generator connected to a power system network.

Applications To Fossil Power Plants: Power plants, due to their large scale and the geographical spread of their components, require more than a single controller to achieve adequate performance. They are naturally decomposed into subsystems. For each of these subsystems a single controller can be designed to achieve a set of objectives. However, due to the coupling between the subsystems, and the potential conflicts between their performance objectives, there is a need for coordination to ensure that local objectives are not met at the expense of global ones. The need for a coordinator becomes even greater if faults or significant disturbances are to be accommodated. A coordinator capable of achieving these demanding objectives needs to have a high degree of autonomy and, hence, some level of intelligence. A fuzzy-logic based intelligent coordinated control scheme was developed to provide autonomy.[32-35] The fossil plant is decomposed into three main subsystems, boiler, turbine, and generator subsystems, Figure 6. Each of the subsystems is equipped with a local controller dedicated to meet the local objectives with no special considerations to the global ones. An extended Kalman filter is utilized to observe the states of the nonlinear plant on-line. The Kalman filter estimates are compared to the states of a nominal model to generate the difference or residuals. A fuzzy logic-based coordinator monitors the residuals and diagnoses for possible disturbances. If a malfunction is detected, the coordinator modifies the local controllers' set points to accommodate it. This approach enables the design of local controller independent of global objectives, and the local controllers are designed by using the model-based optimal and robust LQG/LTR approach and the genetic algorithms.

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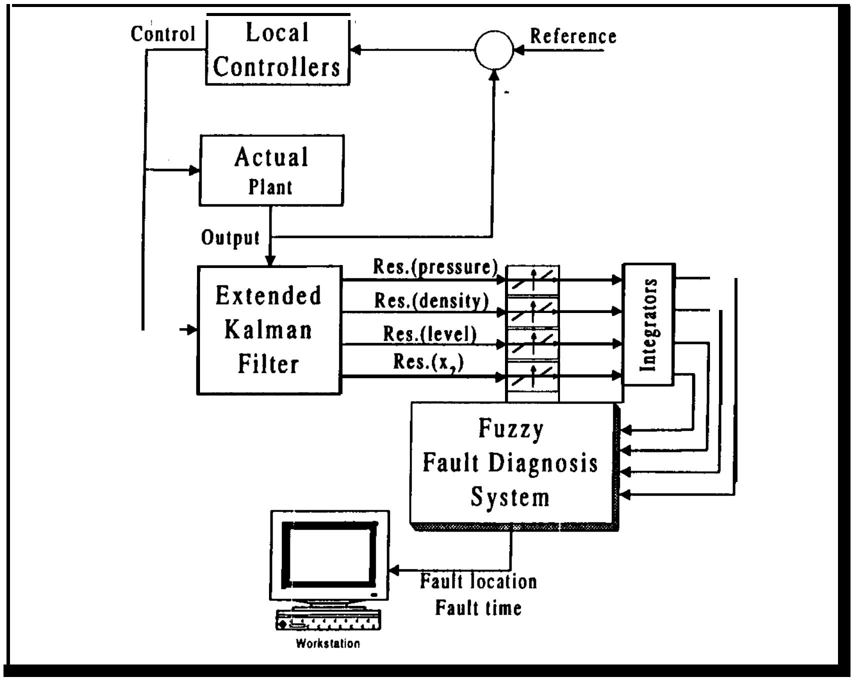

Figure 6. Functional block diagram for fault diagnosis.

Applications To Nuclear Plants: Model-based, fuzzy logic, and neural network control were also all studied for application to nuclear reactor control.[36-41] The dynamics of a reactor in a power plant is nonlinear and thus its control for wide-range operation may benefit from the application of intelligent control approaches which have the capability to learn or adapt to the environment. In order to systematically study and compare different approaches, the optimal control, the LQG/LTR robust control, neural network control, and fuzzy logic control, to reactor control, a specific control objective to improve the unmeasurable reactor fuel temperature to provide a faster response without overshoot was studied. Genetic algorithm was fully used in designing a hybrid feedback-feedforward controller for steam generator in order to provide a wide range of operation.[24]

CONCLUSION

A brief overview has been presented for the now completed NSF supported Combined Research and Curriculum Development for Power Plant Intelligent Distributed Control, NSF EID-92121 32. The principal new curricula development included two new graduate level courses on “Power Plant Dynamics and Control” and “Intelligent Distributed Control for Power Plants.” Over 30 research publications were prepared and six M.S. and four Ph.D. degrees were earned. The ready availability of research activities and results provided for especially meaningful courses to be conducted, and the courses provided a systematic mechanism to introduce and train new students for subsequent research, We believe this combined research and curriculum development approach has been exceptionally productive and will be continued in our future work.

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