SECOND ANNUAL TECHNICAL PROGRESS REPORT
for the period Sept. 1990 to Sept. 1991
INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS
(DOE GRANT DE-FG07-89ER12889)

PRINCIPAL INVESTIGATOR:
Edward H. Klevans

ADDITIONAL INVESTIGATORS:
Robert M. Edwards
Asok Ray
Kwang Y. Lee

STUDENT INVESTIGATORS
H.E. Garcia
C.M. Chavez
J.A. Turso
Adel Ben Abdennour

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1.0 SUMMARY:

In September of 1989 work began on the DOE University Program grant DE-FG07-89ER12889. The grant provides support for a three year project to develop and demonstrate Intelligent Distributed Control (IDC) for Nuclear Power Plants. The body of this Second Annual Technical Progress report covers the period from September 1990 to September 1991. It summarizes the second year accomplishments while the appendices provide detailed information presented at conference meetings.

There are two primary goals of this research. The first is to combine diagnostics and control to achieve a highly automated power plant as described by M.A. Schultz, a project consultant during the first year of the project.\textsuperscript{1,2} His philosophy, as presented in the first annual technical progress report, is to improve public perception of the safety of nuclear power plants by incorporating a high degree automation where a greatly simplified operator control console minimizes the possibility of human error in power plant operations. A hierarchically distributed control system with automated responses to plant upset conditions is the focus of our research to achieve this goal. The second goal is to apply this research to develop a prototype demonstration on an actual power plant system, the EBR-II steam plant.
2. BACKGROUND:

Yearly milestones were identified in the original proposal. The first year milestone was to demonstrate a steam cycle diagnostic operating on-line at the EBR-II plant in a single SUN computer and this has been accomplished. The second year milestone was to demonstrate distributed diagnostics on-line at EBR-II and the third year milestone is demonstration of distributed control acting on the input provided by the distributed diagnostics. As will be discussed later, completion of the 2nd year milestone to be achieved during the summer of 1991 was deferred to the last year because of EBR-II priorities (TIGER team visit and review). However, a distributed diagnostic is operational in the controls laboratory at Penn State.

The potential benefits of this research are the identification and evaluation of techniques for safer and more reliable nuclear power plant operation as well as education and training of students in advanced control techniques. Although the third year prototype demonstration of intelligent distributed control will be at an experimental power plant facility, the ultimate benefit will come from incorporation in existing and future commercial nuclear power plants. Since this project was initiated in 1989, the need to upgrade existing Nuclear Power Plant I&C systems has come to the forefront. In 1991 the Electric Power Research Institute and
Nuclear Utility Industry initiated a program with the goal of modernizing at least 10 existing U.S. nuclear power plants by the year 2000.

The main relationship of this research to existing DOE programs is through EBR-II which is operated by the Argonne National Laboratory. EBR-II's current emphasis is on demonstration of the Integral Fast Reactor (IFR) concept but one of their secondary objectives is development and demonstration of Advanced Control & Diagnostic System Technology. Over the last few years, the Experimental Breeder Reactor II has been conducting modernization of their plant under an Advanced Control and Diagnostic System Technology Program. In the mid 1980s they added a Digital Data Acquisition System with monitoring capability for about 1000 points. They also replaced some obsolete analog controls with a distributed microprocessor-based control system, a Bailey NETWORK 90 system. Most of these digital controllers were added to the steam side of the plant. (On the primary system, the microprocessor based controllers are used for primary pump speed control.)

EBR-II has pioneered the development of graphics-based displays of plant information using UNIX based DATAVIEWS Software. In 1991, EBR-II is also modernizing their Cover Gas Cleanup System (CGCS) with a distributed microprocessor-based
system interfaced to a graphics-based operator console. A feature of the EBR-II steam plant which enables the efficient development of a prototype intelligent control experiment is that they already have in place a digital data acquisition system and distributed microprocessor-based control system. Through a major NSF equipment grant a Bailey NETWORK 90 microprocessor-based control system was incorporated in a unique university laboratory at Penn State during the first year. In this second year of the DOE project, a Concurrent 6350 real-time UNIX-based computer system was added to the lab. The Intelligent Distributed Controls Research Laboratory (IDCRL) now has complete compatibility with EBR-II hardware and software systems and is demonstrating distributed intelligent control experiments for EBR-II.

First year tasks accomplished and reported in the First Annual Technical Progress Report were: 1) Simulation of the EBR-II steam plant, 2) development of steam plant diagnostics, 3) simulation testing of diagnostics, 4) demonstration of diagnostics at EBR-II, 5) evaluation of improvements for diagnostics, 6) plant design for automatic control, and 7) learning systems reconfigurable control.
3. SECOND YEAR ACCOMPLISHMENTS

The 7th task of the first year was an extra task beyond the originally proposed activities and was added as more understanding of the details needed to accomplish the desired demonstration became better understood. Similarly, another task in addition to those identified in the 2nd year continuation proposal (May 1990) was adopted during the 2nd year, robust fault-accommodating controller design. The 2nd year tasks in order of completion are: 1) learning systems demo programmed in a Bailey Multifunction Controller (MFC), 2) robust fault-accommodating controller design, 3) VAX Cluster <-> UNIX network distributed simulation, 4) Programming of Schultz's automatic control, 5) distributed diagnostics, and 6) verification and validation.

3.1 Learning Systems Demo Programmed in a Bailey MFC

The learning systems task, initiated as task 7 in the first year, demonstrates a reconfigurable control approach to accommodate system faults. Specifically, this technology has been developed to accommodate a hypothesized failure of the steam supply to the EBR-II number 2 feedwater heater, a deaerating heater\textsuperscript{3,4} (Appendix B.2). To accommodate such a failure, the learning systems algorithm selects an alternate control law for pressure regulation using the condensate flow control valve. The effectiveness of this type of action has been demonstrated using a variety of simulation techniques
including real-time simulation using an IBM 4341, batch mode simulation using a VAX computer, and real-time simulation using a VAX interfaced to the Penn State Bailey NETWORK 90 microprocessor-based control system.

The 2nd year activity in this area implemented the learning systems algorithm in the C computer language down-loaded in a Bailey Multifunction controller. Classical Proportional-Integral (PI) control laws for normal level regulation or alternative pressure regulation using the condensate valve are programmed using standard Bailey control blocks and the learning systems algorithm simply selects the control law to enforce based on the performance of the deaerator.

Figure 1 presents a Bailey CAD drawing outlining the structure of the learning systems reconfigurable control within the Bailey MFC. The execution of the general purpose C language programming of the learning algorithm is symbolically represented by the Invoke-C block on the drawing. In the current testing and demonstration configuration, the Bailey MFC receives simulated deaerator pressure and level from a VAX simulation (indicated at the left edge of Figure 1). Valve position commands determined by the MFC are sent to the VAX simulation (indicated at the right edge of Figure 1). A Bailey MFC programmed with this reconfigurable control demonstration can in principle be deployed at EBR-II by substituting the
actual plant signals for deaerator pressure and level and
directing the MFC valve position commands to the actual plant
actuators.

3.2. Robust Fault-accommodating Controller Design

Control system fault-accommodating behavior is considered
essential for safely achieving the level of complete power
plant automation identified by M.A. Schultz. Schultz’s concept
for EBR-II, as outlined in an addendum report to the first
annual report,

 describes a CRT based control system with a
simplied operator interface for directing control of the
plant which is limited to 8 functions. To accomplish such a
simplified interface for operating a plant requires a system
which can automatically start-up and shut-down as well as take
care of itself during faulted conditions, fault-accommodating
control. The learning systems approach to reconfigure control
is one element of such an intelligent control concept. Another
complementary approach to achieve fault accommodation is to
apply robust multivariable control design to improve
conventional PI control algorithms already deployed at EBR-II
and most other commercial nuclear power plants.

The 2nd year task added in this area applied existing
multivariable robust control theories (LQG/LTR) to design a
model-based controller to directly accommodate the hypothesized
failure in EBR-II deaerator steam supply. The model-based
controller, which incorporates a multivariable optimal control law for deaerator level and pressure, simultaneously uses both control actuators (steam valve and condensate valve) to jointly control deaerator pressure and level. With a failure in the steam supply, the condensate valve is used directly in mitigating the pressure loss without the need to reconfigure or switch between control laws. To maximize fault-accommodating capability for a system, a reconfigurable controller, as in the learning systems task, can select between preprogrammed multivariable robust control algorithms instead of being restricted to simple PI control algorithms.

This robust fault-accommodating control design task was undertaken as the master of science thesis of Electrical Engineering student Adel Ben-Abdennour. The thesis was completed during the last quarter of the 2nd year (summer of 1991) with receipt of degree in December 1991. An approach to incrementally adding the model-based controller to the existing Proportional Integral (PI) controlled plant was also examined. The concept of using an embedded classical controller within a model-based controller was pioneered by R.M. Edwards (Appendix B.1)\textsuperscript{5} in his PhD dissertation\textsuperscript{6} for a Single-Input Single-Output robust reactor power controller. This dissertation provides an approach for application of modern control theory as an element of intelligent distributed control. In Schultz's addendum report for an automatic control system for EBR-II\textsuperscript{2}, he
describes how the higher level supervisory control system forwards demand signals to the lower levels in the hierarchy to achieve normal automated start-up, shutdown, and power level maneuvers. Fault accommodating set-point modification to lower-level controllers may be similarly conducted using a model based controller at a coordination level and will be a 3rd year activity.

A paper jointly describing Edwards' and Ben-Abdennour's work was presented at an EPRI Conference in April 1991\(^7\) (Appendix B.3) and a 2nd paper on Ben-Abdennour's application to EBR-II was presented at the AI 91 Conference\(^8\) (Appendix B.7).

3.3 VAX Cluster <-> UNIX Network Distributed Simulation

The development of a simulation methodology to achieve a plant-wide real-time simulation testing capability was also reported at the EPRI Conference in April 1991\(^9\) (Appendix B.4). This capability is achieved by using decomposed simulations of the plant operated on different VAX computers in the Engineering Computer Lab at Penn State. The real-time distributed simulation is coordinated through a real-time UNIX workstation, Concurrent 6350. In April 1991, the EBR-II feedwater and condensate system were operated in the distributed simulation configuration. Since then, the EBR-II steam generation system (evaporators, steam drum and
superheaters) has also been integrated with the distributed simulation. Thus, a real-time simulation testing capability for the EBR-II steam plant based on the validated batch mode simulation accomplished by Ruhl\textsuperscript{10} in the first year is now completed and was reported by Garcia at the AI 91 conference\textsuperscript{11} (Appendix B.8).

The 6350 UNIX workstation will also be interfaced directly to the Penn State Bailey System in the final year. This interface can examine both serial and IEEE 488 parallel interfaces to the Bailey System. This direct interface will also replace the initial serial interface directly from the VAX computer system used for the learning systems demonstrations conducted thus far for the project. The direct serial or IEEE 488 parallel interface between the Concurrent 6350 and Bailey system is also expected to be used in conducting the proposed demonstrations at EBR-II.

3.4 Programming of Schultz’s Automatic Control

The initial programming of the operator interface for the simplified controls of the intelligent distributed control demonstration has been conducted by Carlos Chavez as part of an Industrial Engineering course project in Human/Computer Interface Design. The initial interface primarily addressed the operation of the up and down pushbuttons that allow the operator to select the power level for the plant. The
interface utilized the existing EBR-II main iconic display of plant information (Figure 2a) and generates a simulated display of the 8 control function console. As the operator selects the desired power level, the expected plant temperature distribution is overlayed on the main iconic display, Figure 2b. As the plant is maneuvered to the new power level, the actual temperature distribution can be easily compared to the target temperature distribution in order to convey the performance of the plant and controls to the operator. This initial interface was implemented on a PC computer as part of the Industrial Engineering course requirement.

During the summer of 1991, the interface was converted to DATAVIEWS software implementation in the EBR-II main iconic display which is currently operational on the Penn State 6350 Concurrent Computer. This interface is now used by Penn State researchers to oversee the operation of the distributed simulation testing environment in the final year of the project. Mr. Chavez presented a paper at the AI 91 conference on this aspect of the project12 (Appendix B.9).
Figure 2. A) EBR-II Main Plant Display  B) Simulated Control Panel
3.5 Distributed Diagnostics

The 2nd year milestone of an in-plant demonstration of distributed diagnostics was not possible in the summer of 1991 because EBR-II was consumed with a TIGER TEAM Review. The distributed diagnostic was, however, operational in our controls lab at that time and is being developed for an in-plant demonstration in the final year. Local diagnostics are conducted at the microprocessor-based level to perform elementary performance evaluation of a process control loop. Additionally, the DISYS diagnostic system performs a complementary overall system status assessment from a centralized operation in a UNIX computer. The results of this global and redundant process diagnostic is distributed to the local intelligent controllers operating at the microprocessor-based level.

This aspect of the project was presented at the AI 91 meeting by Garcia^11 (Appendix B.8).

3.6 Verification and Validation

Verification and validation of proposed 3rd year experiments will follow the established EBR-II Experiment Guide. The first step will be the preparation of a Technical and Program Feasibility Design Package.

In order to gain practical experience at conducting real-
world experiments with Bailey Microprocessor-based controllers, a reactor optimal control algorithm described by Edwards (Appendix B.1)\(^5\) was adapted for implementation on the Penn State TRIGA reactor. Prototype experiments have now been conducted and reported at the AI 91 meeting by Turso\(^13\) (Appendix B.10). The TRIGA experiment develop sequence also includes hardware-in-the-loop simulation testing of the optimal control algorithm prior to the in-plant (TRIGA) experiment and is therefore analogous to the development of the intelligent distributed control experiment under development for EBR-II. This commonality suggests the possibility for stronger development of advanced control concepts for commercial nuclear power plants by first selecting an application which can be demonstrated on all facilities (i.e., the optimal reactor temperature control algorithm) and then progressively demonstrating it in more complex situations: TRIGA, EBR-II, and finally for commercial nuclear power plants.

4. CONCLUSIONS

Very good progress has been maintained on the project during the 2nd year. Postponement of the 2nd year demonstration milestone at EBR-II as part of the 3rd year experiments should provide for better experiment continuity and better utilization of both Penn State and EBR-II personnel. The hardware-in-the-loop simulation testing setup for EBR-II steam plant applications is completely functional. However, a
better direct connection between the Bailey distributed controllers and UNIX-based distributed simulation coordination computer will be developed and also used in actual in-plant experiments.

The major tasks for the third year are to expand this approach to the automation on a larger scale to the EBR-II steam plant: 1) verification of distributed simulation results with actual EBR-II plant data and preparation of the design package for the intelligent distributed control demonstration, 2) robust fault accommodating control design for the steam generation subsystem and overall steam plant, 3) reconfigurable control and automated decision making strategies for the steam generation subsystem and hierarchical intelligent distributed control to coordinate the deaerator and steam generation subsystems, 4) integration of steam plant automation and diagnostics in an operator interface within the established EBR-II UNIX workstation displays and 5) improvements to diagnostics developed during the first two years will continue to be identified and implemented as necessary.
5. REFERENCES:


DATE FILMED
01/20/1993