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DISTRIBUTED AND HIERARCHICAL CONTROL TECHNIQUES FOR LARGE-SCALE POWER PLANT SYSTEMS

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ABSTRACT

In large-scale systems, integrated and coordinated control functions are required to maximize plant availability, to allow maneuverability through various power levels, and to meet externally imposed regulatory limitations. Nuclear power plants are large-scale systems. Prime subsystems are those that contribute directly to the behavior of the plant's ultimate output. The prime subsystems in a nuclear power plant include reactor, primary and intermediate heat transport, steam generator, turbine generator, and feedwater system. This paper describes and discusses the continuous-variable control system developed to supervise prime plant subsystems for optimal control and coordination.

INTRODUCTION

The research work reported in this paper is intended to convey a philosophy for the design of large-scale control systems that will guide control engineers and managers in the development of integrated, intelligent, flexible control systems. Overall system integration is a natural goal for the control engineers of a large-scale plant system because the scope of control should encompass the entire plant. Integrated and coordinated control of large-scale systems is required to maximize plant availability, to allow maneuverability through various stages of degradation, and to meet externally imposed regulatory limitations.

A nuclear power plant is a large-scale system. The subsystems that constitute a nuclear power plant can be classified according to their functional relationship to the overall plant and according to the type of control required to make them operational. Thus the plant is composed of prime systems, support systems, and utility systems. Within these classifications, systems can be further divided into those that exhibit continuous and discontinuous behavior. Prime systems are those that contribute directly to the plant's ultimate output. In a nuclear power plant, the prime systems may constitute reactor, primary and intermediate heat transport, steam generator, turbine-generator, and feedwater system. Support systems are those that supply necessary functions and services to the prime systems of the plant. Utility systems are, in a sense, also support systems. They are the common services that supply bulk materials, energy, or data to the prime and support systems.

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Further classification of the plant's prime, support, and utility systems will prove useful when applying control to coordinate plantwide changes in mode. It is useful to identify the subsystem type by the way the system is called into operation and the states it assumes. Two classes of system control are then proposed: continuous and discontinuous. To automate a large-scale system, both classes of control must be integrated to carry out the functions required to achieve the goals and objectives of the entire plant. Subsystems that exhibit continuous parameter variation, and thus may be controlled proportionally, fall under the continuous control category. In general, the continuously controlled subsystems lie within the prime plant systems. This form of control is the type most often associated with control engineering. The fields of classical and optimal control theory are directed primarily at the control of continously variable systems.

The second category--discontinuous control--refers to subsystems that exhibit discrete operational states and are called on to function by an enabling command with no element of proportionality contained in the command. (However, within a subsystem enabled by a state-oriented command, local control loops may function in proportion to measured values. These loops, however, are hidden from the subsystem's superordinate.) A discontinuously controlled subsystem may be off-on or start-stop in operation, or there may be a limited number of additional control modes in which it may be commanded. Batch control, logical control, mode control, and sequence control are forms of discontinuous control.

This paper discusses the continuous-variable control system that supervises prime plant subsystems for optimal control and coordination.

The distributed and hierarchical control system outlined here is designed to improve overall plant dynamics and achieve the following objectives:

1. high reliability and availability of the plant;
2. coordination of plant control during normal operation, low power level operation, and contingencies;
3. efficiency of plant operation through tightened control at the local subsystem level; and
4. hardware and software flexibility for later modification.

DESCRIPTION OF DISTRIBUTED AND HIERARCHICAL CONTROL OF LARGE-SCALE SYSTEMS

Distributed and hierarchical control systems have evolved over the past few years as a natural outcome of the need to classify process control functions by process area and the level of control function, and because of the availability of microprocessor-based computers for local controllers. This evolution has occurred as processes have become increasingly large and complex, leading to more stringent demands on control system performance. Similar to the management of a large corporation, industrial control systems have acquired the characteristics of distributed and hierarchical organization.

A large-scale system may be described as a complex system composed of a number of constituents or smaller subsystems serving particular functions and governed by interrelated goals and constraints. One of the interactions among subsystems is hierarchical; that is, a subsystem at a given level controls or coordinates the units on the level below it and is, in turn, controlled or coordinated by the unit on the level immediately above it.

A large-scale system can be controlled hierarchically by dividing (decomposing) it into a number of subsystems and then coordinating the resulting subsystems to transform a given integrated system into a multilevel one [1,2]. Figure 1 shows a distributed hierarchical system with continuous and discontinuous control. This structure allows modularization, which increases the reliability of the system, improves flexibility for later modification, and facilitates troubleshooting. It also makes it possible for each function to be independently designed, engineered or programmed, tested, debugged, and documented.

THE INTERACTION PREDICTION APPROACH FOR DESIGNING DISTRIBUTED AND HIERARCHICAL CONTROL SYSTEMS

The chosen objective is to design a control system for a large-scale nuclear plant with load-following capability. Due to the load demand from supervisor, the basic control approach adopted is to design a regulator control coupled with a feed-forward action. Then a distributed and hierarchical control coordinator is designed using an interaction-prediction approach [1,2]. This method uses a linear model of the process and a linear quadratic performance criterion (decision rule) to design optimal controllers for the subsystems, taking into consideration interactions between subsystems. The interaction prediction method provides an overall optimal control for the total plant with much reduced computations. The linear model [3]

$$\dot{X} = AX + Bu \quad , \tag{1}$$

is based on the assumption that the feed-forward controller keeps the plant to the desired steady-state program. Matrices A and B are generally dependent on the power level. If A and B are evaluated at a setpoint (operating power level), they are constant matrices. If load following is desired over a broader range, one may have to evaluate the A and B matrices at the middle of the range or at several points along the load range and use those values.

Feed-forward control can speed up plant response, but regulator control is needed to bring the plant parameters (e.g., steam chest pressure and temperature) to desired values. Thus, a linear feedback optimal controller is designed by minimizing a quadratic performance index of the form

$$J = \frac{1}{2} X'(T)Q\, X(T) + \frac{1}{2} \int_0^T [X'QX + u'Ru]dt \quad , \tag{2}$$

where T is the terminal time, 1 is transpose, and Q and R are weighting matrices chosen by the designer from experience or through simulation studies.

A linear feedback controller designed in such a fashion will allow the plant to follow the load demand and keep the plant parameters at the desired values.

Method

Consider a large-scale linear interconnected system, described by Eq. (1), decomposed into N subsystems, each of which is described by

$$\dot{X}_i(t) = A_i X_i(t) + B_i u_i(t) + C_i Z_i(t) \ , \ X_i(o) = x_i(o);, \ i = 1, 2, \ldots N \tag{3}$$

where the interaction vector Z_i is

$$Z_i(t) = \sum_{j=1}^{N} L_{ij}X_j \quad . \tag{4}$$

One can consider that the actuator dynamics are also included in the subsystem model. For a large reactor system these subsystems are reactor, intermediate heat exchanger (IHX), steam generator, turbine, and feedwater. The optimal control problem at the first level is to find a control $u_j(t)$ which satisfies Eqs. (3) and (4) while minimizing a quadratic cost function.

$$J_i = \frac{1}{2} X_i' (T)\, Q_i X_i(T) + \frac{1}{2} \int_0^T (X_i' Q_i X_i + u_i' R_i u_i)dt \quad . \tag{5}$$

J_i is i^{th} component of J in Eq. (2). With the interconnection equation incorporated into a Lagrangian, the Lagrangian becomes

$$L = \sum_{i=1}^{N} \left\{ \frac{1}{2} X_i' (T)\, Q_i X_i(T) + \frac{1}{2} \int_0^T \left[X_i' Q_i X_i + u_i' R_i u_i \right.\right.$$

$$\left.\left. + \lambda_i' \left(Z_i - \sum_{j=1}^{N} L_{ij}X_j \right) + P_i' (-\dot{X}_i + A_i X_i + B_i u_i + C_i Z_i) \right] dt \right\} \tag{6}$$

where P_i is the adjoint vector and λ_i is the Lagrange multiplier vector. For given $\lambda_i = \lambda_i^*$, $Z_i = Z_i^*$, L in Eq. (6) is additively separable, that is

$$L = \sum_{i=1}^{N} L_i = \sum_{i=1}^{N} \left\{ \frac{1}{2} X_i'(T)\, Q_i X_i'(T) + \frac{1}{2} \int_0^T \left[X_i' Q_i X_i + u_i' R_i u_i \right.\right.$$

$$\left.\left. + \lambda_i^{*'} Z_i - \sum_{j=1}^{N} \lambda_j^{*'} L_{ji} X_i + P_i'(A_i X_i + B_i u_i + C_i Z_i^* - \dot{X}_i) \right] dt \right\} \tag{7}$$

For the purpose of solving the first-level problem, it suffices to assume that λ^* and Z_i^* are known. The optimal controller for subsystem i is then obtained by Pontriagin's principle

$$u_i = -R_i^{-1} B_i' P_i(t) \tag{8}$$

and

$$\dot{P}_i = -Q_i X_i - A_i' P_i(t) + \sum_{j=1}^{N} L_{ij} X_j \quad , \qquad (9)$$

with

$$P_i(T) = Q_i X_i(T) \quad .$$

Let

$$P_i(T) = K_i(t) X_i(t) + g_i(t) \quad , \qquad (10)$$

$$U_i = -R_i^{-1} B_i^T [K_i(t) X_i(t) + g_i(t)] \quad , \qquad (11)$$

$$\dot{X}_i = [A_i - S_i K_i(t)] X_i(t) - S_i g_i(t) + C_i Z_i(t) \; X_i(o) = X_i(o) \quad , \qquad (12)$$

From the above equations, one can obtain

$$\dot{K}_i(t) = -K_i(t) A_i - A_i K_i(t) + K_i(t) S_i K(t) - Q_i \quad ,$$

with boundary condition

$$K_i(T) = Q_i \quad , \qquad (13)$$

which is the matrix Riccati equation, and

$$\dot{g}_i(t) = -[A_i - S_i K_i(t)]' \; g_i(t) - K_i(t) C_i Z_i(t) + \sum_{j=1}^{N} L_{ij} \lambda_j(t) \; , \; g_i(T) = 0 \quad , \qquad (14)$$

which is the adjoint equation.

The subsystem optimal controller, u_i, is a function of subsystem state X_i (feedback) and the forcing term $g_i(t)$; that is,

$$u_i = -R_i^{-1} B_i^T K_i(t) X_i(t) - R_i^{-1} B_i^T g_i(t) \quad .$$

The optimal controller derived above can be made a completely closed loop with the substitutional g(t) = MX(t) [1].

The second-level problem is essentially updating the new coordination vector

$$\begin{bmatrix} \lambda_i' \\ Z_i \end{bmatrix}$$

which can be obtained from Eqs. (6) and (7),

$$\frac{\partial L}{\partial \lambda_i} = Z_i^* - \sum_{j=1}^{N} L_{ij}X_j$$

$$\frac{\partial L}{\partial Z_i} = \lambda_i^* = C_i P_i(t)$$

thus, making the coordination rule

$$\begin{bmatrix} \lambda_i^* \\ Z_i^* \end{bmatrix}^{K+1} = \begin{bmatrix} -ci \; Pi \\ \sum_{j=1}^{N} L_{ij}X_j \end{bmatrix}^{K} . \tag{15}$$

The technique described is summarized below as a set of procedures which can operate in the software of a control system.

Step-by-Step Procedure

The following step-by-step procedure is suggested for obtaining hierarchical distributed optimal control. Steps 1 and 2 are performed as off-line calculations. The remaining steps (3 through 9) are on-line:

Step. 1. Solve N independent matrix Riccati equations, Eq. (13), with $K_i(T) = Q_i$ and store $K_i(t)$.

Step 2. For initial λ_i^{*k}, Z_i^{*k}, solve adjoint Eq. (14) with $g_i(T) = 0$ and store $g_i(t)$ for all subsystems.

Step 3. Solve state Eq. (12) and store $X_i(t)$ for all subsystems.

Step 4. Compute optimal control u_i for each subsystem using Eq. (11).

Step 5. Compute $P_i(t)$ using Eq. (10).

Step 6. Transmit $X_i(t)$ and $P_i(t)$ to second level.

Step 7. At the second level, update coordination vector $[\lambda_i^*, Z_i^*]'$ using Eq. (15).

Step 8. Repeat the updating of the coordination vector several times until the total system interaction error

$$e(t) = \sum_{i=1}^{N} \int_{0}^{T} \left(Z_i - \sum_{j=1}^{N} L_{ij}X_j\right)' \left(Z_i - \sum_{j=i}^{N} L_{ij}X_j\right) dt/\Delta T$$

is sufficiently small. Here t is the step size of integration.

Step 9. Transmit the updated coordination vector to the first level for each iteration so that new optimal control is computed using an updated coordination vector. Figure 2 illustrates the interaction prediction method of hierarchical control. Consider that at the second level, the computations involve only a calculation of Eq. (15). The lower level does less work

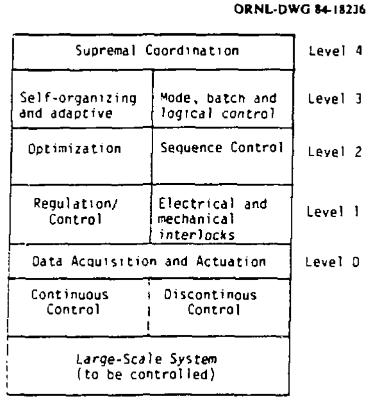

Fig. 1. Functional and hierarchical distribution of continuous and discontinuous control of a large-scale system.

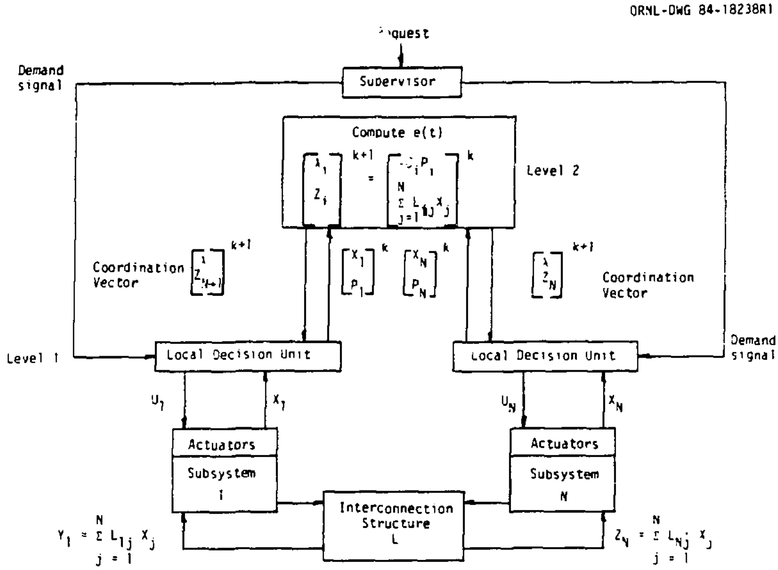

Fig. 2. Interaction prediction method hierachical control.

because problems of lower mathematical order are solved. The convergence is rapid in the iteration process (five or six iterations).

A large-scale plant model usually includes some variables in X that are not measurable. Furthermore, the measured variables are often corrupted by noise introduced by the sensors. There are bound to be discrepancies between real plants and mathematical models. One is then faced with the problem of obtaining an estimate of state for use in the computation of the optimal feedback controller. Several estimation procedures are available in the literature [3,4]. In the case of distributed and hierarchical control, local filters are used to estimate the subsystem state vector [2].

APPLICATION OF DISTRIBUTED AND HIERARCHICAL CONTROL TO THE LARGE-SCALE POWER PLANT

A distributed and hierarchical structure for a large-scale power plant is shown in Fig. 3. This structure includes a supervisory controller, an optimal coordinator, and local decision units (i.e., local process controllers). The general structure given in Fig. 2 is expanded in Fig. 3 to include the specific prime plant subsystems. The supervisor unit provides demand (reference) feed-forward signals to the subsystems. Using hierarchical structure, optimal controllers are designed for each subsystem that take into consideration interaction between subsystems. The hierarchy provides an overall optimal controller for the total plant with greatly reduced computations. A controller designed in such a fashion will allow the plant to follow the load demand requested by the load dispatcher and keep the plant parameters (temperature and pressure) at the desired values.

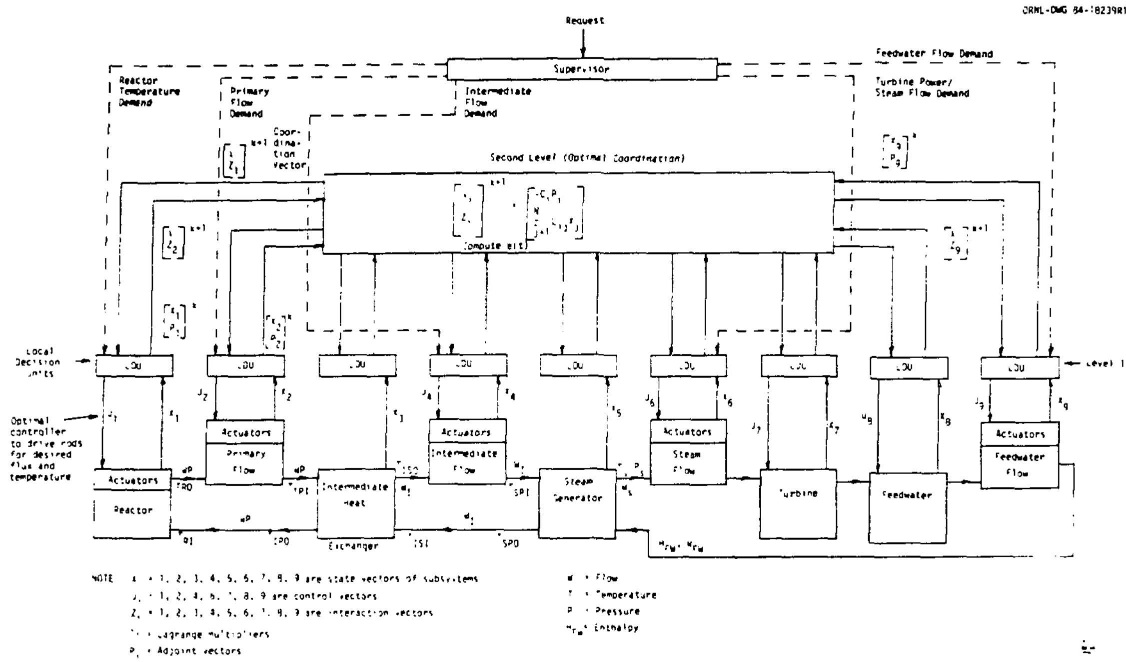

Fig. 3. A distributed and hierarchical structure for a large-scale reactor plant.

CONCLUSIONS

The focus of the control system function and structure presented in this paper is on improved dynamic performance of the plant. The function of the feed-forward supervisory controller and optimal coordinator is to control the minimum error and peak excursion of the subsystem variables. One of the features of the interaction-prediction scheme as it is applied here is the minimization of on-line calculations. The main point to note is that at the second level very little computation work is necessary because the second level evaluates only the right hand side of Eq. (15), which involves a few multiplications. At the first (lower) level, the computations are also less (as compared to regular optimal control methods) because only lower-order subsystem problems are solved. We intend to evaluate the effectiveness of the hierarchical control structure using a modular reactor system model.

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