A Multi-Agent System-Based Intelligent Control System for a Power Plant

Jin S. Heo and Kwang Y. Lee, Fellow, IEEE

Abstract—A large-scale power system has been required to have a new control system to operate at a higher level of automation, flexibility, and robustness. In this panel, a Multi-Agent System based Intelligent Control System (MAS-ICS) is presented as an alternative methodology to control a large-scale power plant. Design of architectures for single agents and an organization of the multi-agent system will be described as the foundation of the intelligent control system. The MAS-ICS has several functions that provide efficient ways to control locally and globally, and to accommodate and overcome the complexity in the large-scale distributed systems. Moreover, it will be shown that the fundamental principle of MAS can be applied well in the large-scale distributed complex power system.

Index Terms—Distributed system, intelligent control system, large-scale system, Multi-agent system, power plant control.

I. INTRODUCTION

As the demand in power increases, newer power plants are being introduced which are getting more complex and expansive to operate. Since power plant is a large-scale system consisting of many subsystems, it is no longer the best solution to manage when using only the centralized control schemes or loosely decentralized control schemes. The reliability of the control system framework, which is highly coupled and interconnected with subsystems, decreases since a single failure can bring down the entire system. In order to overcome these problems, the control system should operate at a higher level of automation, flexibility, and robustness based on a new methodology which can work effectively in the large-scale distributed complex system. Recently, there has been growing interest in multi-agent systems (MASs) in order to deal successfully with the complexity and distributed problems in power systems. Each agent system has special functions to solve the distributed problems. Moreover, in the multi-agent system the agents can work together to solve problems, which are beyond the capabilities or knowledge of an individual agent [1].

There have been many applications of multi-agent systems or agent-oriented systems in control and monitoring systems [2]-[10]. For control purpose, the multi-agent system can help in solving the distributed control problems by cooperative and negotiate control methods [2]-[6]. For monitoring, the multi-agent system can help in monitoring the condition of system and providing effective asset management by diagnostics and protection against faults [7], [8]. Both areas are built upon the multi-agent system properties, such as proactive, reactive, and social properties, as well as other fundamental properties. Moreover, they require highly developed communication protocols and specified architectures for the purpose of applications [9], [10].

A major concern for the networked sensing and actuation of a large-scale system is the complexity, due to the number of components and their interaction patterns and communication delays. This complexity is raised when a control system is required to become intelligent by implementing a completely new variety of knowledge-processing functions. The intelligent system and multi-agent system paradigms, as the state-of-the-art artificial intelligence software engineering concepts, may provide a comprehensive and unifying framework for building the large-scale intelligent control systems. However, a review of the technical literature reveals a lack of design methodologies for multi-agent systems, despite the abundance of tools for other developmental tasks. This points out the need for a new multi-agent system design methodology for the control of large-scale systems such as the power plants.

In this panel, a Multi-Agent System based Intelligent Control System (MAS-ICS) is presented as an alternative methodology to control a large-scale 600MW steam power plant. Design of architectures for single agents and an organization for the multi-agent system will be described as the foundation of the intelligent control system. The MAS-ICS has several functions that provide efficient ways to control locally and globally, and to accommodate and overcome the complexity in the large-scale distributed systems. Moreover, the presented control system will provide an optimal operation as the main goal of the MAS for the large-scale power system utilizing the schemes of a reference governor, modified predictive control, and identification.

Following the introduction, the drum boiler-turbine power plant is described in Section 2. Section 3 describes the design of the architectures for single agents and an organization of the multi-agent system for the intelligent control system. Section 4 describes control functions using the multi-agent based intelligent control system for the power plant. The final section draws some conclusions.

J. S. Heo and K. Y. Lee are with the Department of Electrical Engineering, The Pennsylvania State University, University Park, PA 16802. (email: juhl38@psu.edu, kwanglee@psu.edu).

0-7803-9156-X/05/$20.00 ©2005 IEEE.
II. DRUM BOILER-TURBINE POWER PLANT

A. Development of Power Plant Model

A power plant is a Multiple Input-Multiple Output (MIMO) system and is governed by the unit load demand signal from the central dispatch center. It may also be controlled by the Automatic Generation Control (AGC) signal when the unit is participating in the load-frequency control. A power plant is a large-scale system and its characteristics are defined as following: The dimension of the overall system is very high even if a simple model is used for each subsystem. The dynamics of each subsystem are represented by a set of nonlinear differential equations, and are coupled with nonlinear algebraic equations for interconnection to other subsystems. Operating conditions vary with time continuously, and faults may occur anywhere within the plant or in the network of sensors/actuators at any time.

For power plant control, adequate model is perhaps one of the most essential ingredients in setting up an experiment to test control systems. In general, three necessary characteristics define the degree of the model: (1) it must be reasonably accurate in its representation of the responses of interest, (2) it must be relatively simple, and (3) it must bear close resemblance to physical processes; i.e., the model parameters should be related to physical parameters.

The overwhelming majority of electric power generation is by conventional, drum-type, steam power plants. In this panel, the model has twenty-three state variables associated with physical processes [11]. The model is reorganized into four main modules, which are boiler system, turbine-generator system, condenser system, and feedwater system [12]. The proposed MAS-ICS will be embedded into the model and interconnected with the subdivided and distributed subsystems that are components of the four main modules. Fig. 1 shows the large-scale power plant model and the MAS-ICS. However, the control scheme proposed will be applicable to other types of plants, including nuclear and fuel cell plants.

B. Description of Power System [11], [12]

The power plant is a 600MW oil-filed drum-type boiler-generator unit. It is a balanced draft, controlled recirculation drum boiler capable of delivering $4.2 \times 10^7$ lb/hr of steam at a pressure of 2600 psig and at 1005°F. Six recirculation pumps supply the required recirculation flow to provide sufficient flow for full load operation. Two forced draft fans supply the primary air, and two induced draft fans are controlled to maintain a furnace pressure at a desired preset value. Two condensate pumps and a combined booster and main boiler feedpumps handle the feedwater flow.

The turbine is a tandem compound triple pressure steam turbine. It consists of three parts: a high-pressure turbine, an intermediate pressure turbine, and low twin pressure turbines rotating on a common shaft at a rated speed of 3600 rpm and exhausting a 2 inch Hg absolute. The generator is coupled with the turbine and has a 685,600 kVA, 3 phase, 60 Hz, 22 kV, with a power factor of 0.90.

The developed model represents an extension of some existing models [13]-[15] in two primary areas. First, the condensate and feedwater side dynamics have been modeled and second, the electrical prime movers which run fans and pumps and their dependence upon driving voltage and frequency have been modeled.

Usually, the feedwater and condensate side are ignored on the basis that associated dynamics do not significantly affect the steam side. This assertion is reasonably correct for operations in normal mode. However, the simulations and experience with actual power plants show that the condensate and feedwater dynamics can affect the overall system in various ways. In fact, under certain emergency conditions it is the waterside dynamics that limit the plant response. Therefore, this model can be a prototype for a good target system for control system design.

III. DESIGN OF THE MULTI-AGENT SYSTEM

A. Architecture of Single Agent System

An agent is a computer software program that is autonomous and situated in some distributed environments in order to meet its design objectives. Since the agents are faced with different environments, they are designed differently and
properly for the given environment. Moreover, the agent is intelligent because it is reactive, proactive, social, flexible, and robust. In a large-scale distributed complex system, the agent’s autonomous and intelligent properties can reduce the complexity by reducing the coupling problems between the subsystems. Furthermore, the proactive, reactive, and robust properties can be well suited for applications in a dynamic and unreliable situation [16]-[18].

In order to design the control system, design of architectures for single agent systems and an organization for multi-agent system are required in advance. First, the architecture of a single agent system is shown in Fig. 2. Since the agent is situated in an environment that is the power plant, it needs a perception and effecter to act and react. First, the sensed raw data are processed and mapped into a scenario, and then an objective, which is a sub-goal, is initialized under the situation to achieve the main goal that is the optimal operation. The initial objective is sent to other agents through the communicator for eliminating redundancy and conveying the mission of the agent to others. After confirming the objective, the best plan is chosen for the objective (sub-goal) in the decision-making. Depending on the plan, an algorithm module is selected to lunch the plan. Finally, the action made by the algorithm module effects through the effecter into the environment. Most decisions are made in the decision-making process, which is like in a human brain.

The reactive property of the agent can work well in this mode. Since the large-scale power system is dynamic and unpredictable, the agent should respond correctly and immediately. Beside the perception of the agent, each agent reconfirms whether whose information is true or not by communicating with other agents. Moreover, the agents are distributed in different environment and have their own mode that is considered as a proactive property. The agents not only can work alone by the proactive property under their current sub-goal but also can work together to solve problems, which are required with the cooperation of agents. The social property can be shown with the interaction between the agents and the flexibility is also shown well with various sub-goals to achieve the main goal of the multi-agent system.

Single agent should be able to work independently in the environment and plan how its tasks proceed autonomously. In order to enhance the autonomous ability, the single agent can have multiple algorithms for solving problems. When the agent decides to select one of the algorithms and performs its task, higher-level agents watch and evaluate the performance. Whenever the task or situation is similar to its previous one, the higher-level agent informs the lower-level agent what the best rule is so far. Sometimes, a plan or algorithm module is turned into a fail to achieve the sub-goal. However, the higher-level agents investigate the performance and then the problems are recovered from the failures or worse trials so that the multi-agent system can be more robust. The motivation for the use of the agent-level in multi-agent systems is due to their expected ability to: 1) solve problems that are too large for a single centralized agent; 2) allow the interoperability of multiple existing systems to keep pace with changing needs; 3) provide solutions that efficiently use information sources that are spatially distributed; 4) provide solutions where expertise is distributed; and 5) enhance performance along the dimensions of computational efficiency, reliability, extensibility, robustness, maintainability, responsiveness, flexibility, and reusability [19].

In this panel, the agents are assigned to certain roles for the proactive property as follows:

1) Task delegation agent: This agent, which located at the highest level, monitors the performing jobs of lower level agents and if the tasks are excessive for one agent, it allocates the tasks to different agents in the same level for smooth processes. Since this agent observes and evaluates the lower level agents, it shares the information with other task delegation agents who are in the different hierarchical structure system.

2) Mediate agent: This agent works as a coordinator. When a task is needed that requires the cooperation of agents, it organizes the cluster to process the given mission. Moreover, when an agent of the same or lower level requests information, the mediate agent searches to see if which agent has the information and asks to share the information directly between requesters and responders. The low level agents report the situations and inform their objectives to the mediate agent. This agent has a knowledge-database to store the important data and analyze the data for coordinating the tasks to the low level agents.

3) Monitoring agent: This agent optimally selects, stores, and analyzes the sensing data of the power plant. Since the collected information is stored at its knowledge-database, the monitoring agent has close contacts with agents to share the information.

4) Intelligent agent: This agent has the most important role in implementing MAS-ICS. Since the autonomy of the control system is accomplished based on this agent, it has several algorithm modules for obtaining more optimal operation. The algorithm modules are neural networks algorithms, fuzzy logic algorithms, particle swarm algorithms, evolutionary computation, learning algorithm, and other heuristic algorithms. This intelligent agent works with other agents to establish the set-points and control laws, to identify the
system, to perform multi-objective optimization, and to enhance those tasks more optimally.

Sharing the information with each other and evaluating the performances can achieve optimization for each agent. Although each agent can have the database for processing their tasks, it is proposed to allocate the majority of knowledge-database to the specific agents: mediate agent and monitoring agent. The agents are then loosely connected with other agents that need the information and previous results. However, some restricted information and resources need to be located in each agent. In doing so, the communication and evaluation of agents can be improved, and the excessive tasks and complexity can be reduced by optimization. Moreover, one of the reasons for allocating the majority of data to the specific agents is self-healing and healing other agents. The monitoring agent and mediate agent not only monitor the physical system but also observe performances of the same or lower level agents so that if the agents make an error, then both agents make a plan to overcome the situation and repair the problems of agents. This performance makes the control system more robust in the power plant.

B. Organization of Multi-Agent System

A Multi-Agent System (MAS) can be defined as a loosely coupled network (organization) of problem solvers (agents), which interact to solve problems that are beyond the individual capabilities or knowledge of each problem solver (agent). In order to perform the cooperative works, it is presented to build the MAS-ICS with multiple hierarchical structures for the multi-agent system organization as shown in Fig. 3. The organization has low level, middle level, and high level, and agent in each level has a specific role in the society so that there is a conceptual idea of supervision for processing the tasks. In this panel, the high level agent is the task delegation agent, the middle level agents are the mediate and monitoring agents, and the low level agents are intelligent agents. The hierarchical structure that has three levels gives advantages for dynamic organization, the supervisory concept, and autonomous systems. Moreover, the idea of multiple hierarchical structures is well suited for the large-scale distributed system. Although there are multiple hierarchical structures, each hierarchical structure has a different formation from the others because the structures are constructed to fit for controlling each real physical subsystem in the power plant so that the organization is more optimized for a given power plant system.

A low level agent has communication and coordinative responsibilities over a group of sensors and actuators belonging to a particular functional system component in the power plant. These sensors are non-intelligent sensors grouped in parts, being controlled by the respective agent. The high level agent is a centralized agent, which maintains information about the state of the plant using designed performance matrix. It requests high level information from the lower level agents and is also responsible for middle level agents that coordinate low level agents. The low level agents can form clusters to modularize communication. Agent clustering is introduced to simplify the representation and to indicate that the agents in a cluster use closely related system knowledge or data, and have mutual commitments and beliefs. In reality, all agents may coexist as parallel processes with random access to system information. To optimize coordination, agent clustering techniques will be provided by the middle level agents. The concept of middle level agents is that they function as transactive memories and knowledge repositories for use by the low level agents to decrease data processing overhead over individual agents. Transactive memory theory [20]-[22] examines the process by which individuals determine who knows what and who knows who knows what. Transactive memory systems are a shared cognitive resource for members of a group or team, providing the low level agents with access to more knowledge than any one individual low level agent could possess alone, thereby reducing time and energy spent in the learning process alone.

Multi-agent system as an organization of the agents provides a framework for agent interactions through the definition of roles, behavior expectations, and authority relations. The organizations are, in general, conceptualized in terms of their structure, that is, the pattern of information and control relations that exist among the agents and the distribution of problem solving capabilities among them. The issue of organizational adaptability is crucial. Organizations that can adapt to changing circumstances by altering the pattern of interactions among the different constituent agents have the potential to succeed. An open organization is one in which the structure of the organization is capable of changing dynamically. The information sources, communication links, and components could appear and disappear arbitrarily and unexpectedly. The components may not be known in advance, change over time, and be highly heterogeneous. In open organizations, agents may dynamically find their collaborators based on the needs of the task at hand and on which agents are part of the organization at any given time, thus adaptively forming teams on demand pursuing common goals to achieve global system coherence [23], [24].

The organization of MAS-ICS is provided with (cluster) groups of agents, and the agents are loosely clustered taking the intelligence functions as guidelines as shown in Fig. 3. A generic control cluster takes account of the sequence control, regulatory control, protection, and input-output handling.
agents. A self-awareness cluster is introduced to group the system operating state determination, fault diagnosis, and test assistance agents. The world-modeling cluster comprehends the learning, model building, and adaptation agents. The value judgment cluster comprehends the on-line performance monitoring, control tuning, and reconfiguration agents. The memory cluster is introduced to include the data (sensory) and knowledge processing agents, as well as the system knowledge and data base agents. The behavior generation cluster groups the process optimization, sequence generation, and set-point generation functions.

As required for an open system, the MAS-ICS exhibits organizational adaptability mediated by the supervisory execution manager agent who is mediate agent in the middle level. In principle, the MAS-ICS organization can adapt to changing circumstances by activating or deactivating agents, incorporating new agents or dismissing old agents, or modifying the pattern of interactions among the current agents in the organization. The clusters should be formed adaptively as required.

IV. CONTROL FUNCTIONS OF MAS-ICS

A. Reference Governor

It is proposed to design a reference governor to optimize fuel consumption, pollutant emission, and life of the equipment. The reference governor will produce the multi-objective optimal power plant operation by realizing the optimal mapping between the unit load demand and pressure set-point, and if there is a necessity of mapping to other reference values for local controllers, the reference values will be generated by the reference governor. The intelligent agents are mainly responsible for this module and will work cooperatively with several agents by forming the identifier cluster and the reference governor cluster, which they are the world-modeling cluster and behavior generation cluster respectively. First, an inverse model will be obtained using the identifier cluster. In order to find the best mapping between the unit load demand and pressure set-point, the reference governor needs to obtain the solution space using the inverse model. After that, the reference governor cluster searches the best solution for the optimal mapping in that solution space. Finally, the intelligent agent who manages the learning helps to adjust the optimal mapping by updating the model and preference values or priorities for the multi-objectives. This multi-objective optimization will realize the wide-range operation by following the given single unit load demand profile [25], [26].

B. Predictive Controllers

In order to enhance the optimal operation and robustness, a modified predictive control scheme is proposed as a major control module. The predictive control will work well for the wide-range operation and disturbance rejection. It is implemented by forming the predictive control cluster which is the generic control cluster. The procedure of predictive control scheme is as follows: first, the set points obtained from the reference governor are applied to the feedforward and feedback predictive controllers as reference values. The feedforward predictive controller generates control action based on the set point and the feedback predictive controller initializes an arbitrary control action. The sum of the control actions as a future input value is applied to the trained identifier model [27], which is created by clustering the intelligent agents. The future output values of the identifier of power plant are fed to the feedback predictive controller. The feedback predictive controller regenerates the control action to drive the future output values close to the given reference values. While searching for the optimal control action, the controller analyzes the states from estimator, which is designed by clustering intelligent agents and monitoring agent to reject the disturbance in the power system [28]. Finally, the optimal control action is found and applied to the real power plant through the integrator (delay). The output of the real power plant is fed to the feedback predictive controller and the feedback predictive controller analyzes the set-point, future output, and current output to produce more accurate control action. The intelligent agents will be used for finding the best control action for reducing the error and disturbances when the control action is searched for the given time interval.

C. Identifier

An identifier of a real power plant is required for the predictive controller and inverse model. Generally, the identifier is an approximator, which can be implemented by neural network, fuzzy system, or other intelligent algorithms. The identifier in this panel is assumed to be trained for start-up processing in the power plant. However, during normal operation, the input of the identifier will be changed into the future values, which are different from the input to the real power plant. With intelligent agents and mediate agent, the identifier cluster, which is the world-modeling cluster, can approximate the real power system with the help of these agents. Fig. 4 shows the functionalities of MAS-ICS, which operate by the agents cluster in the power plant.

V. CONCLUSION

A new concept of the intelligent control system based on
multi-agent system is presented for a large-scale power plant. In order to deal with the difficulty of handling a large-scale system, with the added complexity of a network of sensors/actuators, design of architectures for single-agent systems and an organization for Multi-Agent System (MAS) is presented as major solution techniques. Moreover, the MAS-ICS provides several control functions, which are the reference governor, predictive controllers, and identifier by clustering the agents. The reference governor produces multi-objective optimal power plant operation. The predictive controllers perform both prediction and optimization of fuel consumption and load following during normal operation. In order to implement both reference governor and predictive controllers, an identifier is designed. Finally, the MAS-ICS is equipped with a distributed database to allow for learning and self-organization that provide optimal operation in the power system. This feature will make the overall control system adaptive to changes, making it highly autonomous.

VI. REFERENCES


BIographies

Jin S. Heo received his B.S. and M.S. degrees in Electronics Engineering from Inje University, Korea, in 1999 and 2001, respectively. As a candidate, he is currently pursuing the Ph.D. degree in Electrical Engineering at the Pennsylvania State University. His interests are multiobjective optimization in control system, intelligent distributed control, multiagents system, modeling and control of fuel cell power plants, and real-time embedded system.

Kwang Y. Lee received his B.S. degree in Electrical Engineering from Seoul National University, Korea, in 1964, M.S. degree in Electrical Engineering from North Dakota State University, Fargo, in 1968, and Ph.D. degree in System Science from Michigan State University, East Lansing, in 1971. He has been with Michigan State, Oregon State, Univ. of Houston, and the Pennsylvania State University, where he is a Professor of Electrical Engineering and Director of Power Systems Control Laboratory. His interests include power system control, operation, planning, and intelligent system applications to power systems. Dr. Lee is a Fellow of IEEE, Associate Editor of IEEE Transactions on Neural Networks, and Editor of IEEE Transactions on Energy Conversion. He is also a registered Professional Engineer.