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USE OF NEURAL NETWORKS IN THE OPERATION OF NUCLEAR POWER PLANTS

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ABSTRACT

Application of neural networks to the operation of nuclear power plants is being investigated under a U.S. Department of Energy sponsored program at the University of Tennessee.[1] Projects include the feasibility of using neural networks for the following tasks: (a) diagnosing specific abnormal conditions, (b) detection of the change of mode of operation, (c) signal validation, (d) monitoring of check valves, (e) modeling of the plant thermodynamics, (f) emulation of core reload calculations, (g) analysis of temporal sequences in NRC's "licensee event reports", (h) monitoring of plant parameters, and (i) analysis of plant vibrations. Each of these projects and its status are described briefly in this article. The objective of each of these projects is to enhance the safety and performance of nuclear plants through the use of neural networks.

INTRODUCTION

Monitoring and decision making in the operation of a nuclear power plant involves the handling of great quantities of numeric, symbolic, and quantitative information by plant personnel, even during routine operation. The large number of process parameters and systems interactions poses difficulties for the operators, particularly during abnormal operation or emergencies. During such situations, people are sometimes affected by stress and emotion that may have varying degrees of influence on their performance. Taking some of the uncertainty out of their decisions by providing real-time diagnostics has the potential to increase plant availability, reliability and safety by avoiding errors that lead to trips or endanger the safety of the plant. The emerging technology of neural networks offers a method of implementing real-time monitoring and diagnostics in a nuclear power plant.

NEURAL NETWORKS

A network of artificial neurons (usually called a neural network) is a data processing system consisting of a number of simple, highly interconnected processing elements in an architecture inspired by the structure of the cerebral cortex portion of the brain. Hence, neural networks are often capable of doing things which humans or animals do well but which conventional

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computers often do poorly. Neural networks exhibit characteristics and capabilities not provided by any other technology.

Neural networks may be designed so as to classify an input pattern as one of several predefined types (e.g., the various fault or transient states of a power plant) or to create, as needed, categories or classes of system states which can be interpreted by a human operator. Neural networks have the ability to respond in real-time to the changing system state descriptions provided by continuous sensor inputs. For complex systems involving many sensors and possible fault types (such as nuclear power plants), real-time response is a difficult challenge to both human operators and expert systems. However, once a neural network has been trained to recognize the various conditions or states of a complex system, it only takes one cycle of the neural network to detect a specific condition or state.

Neural networks have the ability to recognize patterns, even when the information comprising these patterns is noisy, sparse, or incomplete. Unlike most computer programs, neural network implementations in hardware are very fault tolerant; i.e. neural network systems can operate even when some individual nodes in the network are damaged. The reduction in system performance is about proportional to the amount of the network that is damaged. Thus, systems of artificial neural networks show great promise for use in environments in which robust, fault-tolerant pattern recognition is necessary in a real-time mode, and in which the incoming data may be distorted or noisy.

DIAGNOSTICS: STATE OF THE PLANT

When a nuclear power plant is operating safely, the readings of the hundreds, or even thousands, of instruments in a typical control room form a pattern (or unique set) of readings that represent a "safe" state of the plant. When a disturbance occurs, the instrument readings undergo a transition to a different pattern that represents a different state that may be safe or unsafe, depending upon the nature of the disturbance. The fact that the pattern of instrument readings undergo a transition to a new state that is different for every given condition is sufficient to provide a basis for identifying the state of the plant at any given time. Such identification requires a rapid (real-time), efficient method of "pattern recognition", such as neural networks, to implement a diagnostic tool based on this phenomenon.

Steam Generator Transients. Identification of transients in a U-tube steam generator (UTSG) has demonstrated the ability of a neural network to diagnose specific abnormal conditions in a nuclear power plant.[2] The back-propagation neural network used in this project demonstrated the feasibility of using neural networks to identify six different kinds of perturbations introduced into the UTSG simulator. Furthermore, it gave the correct output even though the input data had very large levels of noise (±90%).

Diagnostics using Watts Bar Training Simulator Data. This technique was then applied to a complete power plant simulation. Data from the new (1989 installation) Singer-Link training simulator at TVA's Watts Bar Nuclear Power Plant for some 27 variables (reduced from 80) for seven different accident transients constitute the input vectors. A special variation of the backpropagation neural network paradigm using a Monte-Carlo training procedure (3) has been very effective in training the neural network to differentiate between the different transients (loss of coolant in the hot and cold legs of the reactor coolant system, main steam-line and main feedwater line breaks in containment, total loss of off-site power, control rod ejection, and steam generator tube leak). In two of the seven cases, the network was able to diagnose the problem before the plant shut down. In all cases, even when noise was introduced into the signals, the neural network was able to diagnose the problem within two minutes of the initiation of the transient. This work is being continued by increasing the number of variables monitored to about 500 (e.g., those available from the safety parameter display system) and by increasing the number of accident transients to cover all those normally used in the training of nuclear plant operators.

Detection of the Change of Mode in Nuclear Power Plants. During operation of a nuclear power plant, it is desirable to identify changes in the state of operations at the earliest possible time. With the fluctuations that take place during normal operations, there is often a period of minutes before deviations are identified clearly, even when the operators continuously watch the appropriate instruments. In this project, two neural network techniques were applied to data from a commercial pressurized water reactor nuclear power plant to detect changes in the states of the plant's operation. Both the polynomial discriminant method and the backpropagation method were able to classify correctly over 97% of the patterns, thereby identifying the correct mode of the plant.[4] On-line identification of modes appears to be feasible.

MONITORING OF NUCLEAR POWER PLANTS USING NEURAL NETWORKS

Sensor Validation. The usefulness of information provided to plant operating personnel is dependent upon the validity of the signals coming from sensors as well as the ability to convert such data into meaningful information, presenting it in an understandable format, and providing a diagnosis of the problems. A neural network paradigm has been developed for automated sensor validation during both steady-state and transient operations. [5] The use of neural networks for signal estimation has the advantage that the functional form relating a set of process variables is defined by the neural network system (model) and is implicitly nonlinear. Once the network is properly trained, future predictions can be made in real-time. The state estimation using a neural network is less sensitive to measurement noise compared to direct model-based techniques. As new information about the system becomes available, the network connection weights can be updated without relearning the entire data set.

For signal validation, the input layer of artificial neurons correspond to the input signals and the output layer may have just one signal which is to be predicted or estimated. Tests with data from the EBR-II liquid metal fast breeder reactor at the Idaho National Engineering Laboratory and a commercial four-loop pressurized water reactor have shown that this technique can be used to validate data from sensors placed in nuclear power plants.[5]

Monitoring of Feedwater Venturi. The techniques discussed above for sensor validation can be extended to monitoring a specific variable for drift or change over time. A specific application being initiated involves monitoring the fouling of the venturi that measures the feedwater flow to the steam generators in a nuclear power plant. Since this measurement is directly related to the calculation of thermal power, fouling effectively causes a derating of the plant from the licensed power level, unless it can be evaluated and compensating steps taken. A feasibility study is being undertaken to determine if the techniques developed at the University of Tennessee [6] can provide the required detection and evaluation of this fouling.

Monitoring of Check Valves. Check valve failures at San Onofre Unit 1 on November 21, 1985 led to the Nuclear Regulatory Commission (NRC) issuing NUREG-1190 that discussed the reasons for the failures of the five check valves and how the check valve failures induced water hammers to the feedwater system. Although there are many failure mechanisms possible for check valves, the most common problems associated with check valve failures are due to system flow oscillations or system piping vibrations. These oscillations and vibrations induce check valve component wear and thus component failure. The most common types of physical damage in check valves (disc separated from the hinge pin, disk stud broken, disk nut loose, disc partially open, disk caught on inside of the seat ring, antirotation lug lodged under hinge arm, cracked disc, seat ring, or bushings, worn hinge pin and bushings, missing bushing, elongated hinge pin holes, and bent hinge pin, disc, and hinge arm) give some kind of evidence of their existence. Many of them emit sounds that can be detected by monitoring acoustical emissions from the valve body. Inappropriate movement of the disc can be detected by magnetic or ultrasonic measurements or through movement (displacement, velocity or acceleration) devices attached to the disc.

Neural networks have the ability to recognize patterns and extract complex statistical features from the data they process. A program involving use neural network techniques for the analysis of acoustical data from check valves has been initiated. It involves training the system to recognize predefined conditions and using the system for data clustering based on the inherent statistical features of the data. Preliminary work is underway on the basis of contemplated funding, and the results are encouraging. However, the success of this project is directly related to securing data from many check valves of different sizes and types that are both operating properly and malfunctioning in order to associate patterns with the known condition of the check valves.

Monitoring of Thermodynamic Performance. About 30 measured variables used to determine heat rate (inversely related to efficiency) at TVA's Sequoyah Unit-1 Nuclear Power Plant for about 60 weekly measurements was used to develop a neural network model of the thermodynamic processes of the plant. [6] When the original data were introduced into this model for recall, the results were usually within 0.1 % of the measured values. When the data from Unit-2 (a very similar, but not identical unit) was put into the network, the output heat rates usually agreed within 0.5% of the measured values. The neural network model was then used to carry out a sensitivity analysis to determine how changes in the different variables influence the heat rate. The sensitivities of the changes in heat rate under different conditions can give guidance to the utility as to which efforts to improve efficiency are most cost effective.

Design of Nuclear Fuel Cycle Reload. This project combines an expert system and neural networks to improve the efficiency for obtaining optimal candidate reload core designs.[6] Neural networks capture the essential physics of the neutronic calculations by training the networks to produce the same results as the conventional calculations. Separate neural networks are used to emulate the LEOPARD code, the neutronic statics calculations and fuel depletion calculations. An expert system then performs fuel shuffling that produces an improved core loading. Several iterations of this process will give a near optimal candidate fuel loading. Although NRC approved calculational methods must still be used for licensing, this approach, when developed, promises to be much faster and less expensive than present methods.

Review of "Licensee Event Report" Data Base. When there is an incident of any sort at a commercial nuclear power plant in the United States, the utility must sent a "licensee event report" (LER) to the Nuclear Regulatory Commission (NRC).[6] ORNL has processed thousands of these reports for the NRC in the past several years by encoding the sequence of events from each incident into a computerized data base. Self-organizing neural network techniques are now being applied to determine if hitherto undiscovered correlations can be identified. At the present time, a prototype network is being developed and several hundred events are being studied. This project constitutes a "mining of the data base for 'nuggets' of knowledge."

Analysis of Vibrations. Although the flow of fluids (water and steam) can induce vibration and shock, the primary source of vibration is rotating machinery. Vibration *per se* is not necessarily bad if its amplitudes and the associated forces are within acceptable limits. Indeed, vibration in machinery can be the source of much information about the various systems involved. Analysis of vibration data can identify the operational problems of rotating machinery. Such analyses have proven very effective in identifying potential failures before they occur. Indeed, it is now possible to estimate the remaining life of certain systems, once a fault has been detected. Hence, there is considerable motivation to design systems to automatically perform this analysis on a real-time basis in a reproducible manner.

A program for the analysis of vibration data been initiated that involves the application of neural network technology to the automation of the processes that typically require expertise to interpret the measurements. This approach involves both training the neural networks to recognize predefined conditions and using the networks for data clustering based on the inherent statistical features of the data. The preliminary work has been encouraging.

CONCLUSION

In the light of the experience described above, it is clear that neural networks offer an interesting and productive means of addressing many of the problems that occur in nuclear (and fossil) power plants. Although much of this work is still in the feasibility stage, the results indicate that the techniques can be used to enhance the performance and safety of nuclear power plants.

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